Aalto University
School of Engineering

Camilla Tuomela

Modelling Source Area Contributions of Stormwater Pollutants for Stormwater Quality Management

Master's thesis for the degree of Master of Science in Technology submitted for inspection

Espoo 8.9.2017
Supervisor: Professor Harri Koivusalo
Instructors: D.Sc. Nora Sillanpää, M.Sc. Perttu Hyöty and M.Sc. Timo Nikulainen

Aalto University
School of Engineering

Aalto University, P.O. BOX 11000, 00076 AALTO
www.aalto.fi

Abstract of master's thesis

Author Camilla Tuomela

Title of thesis Modelling Source Area Contributions of Stormwater Pollutants for Stormwater Quality Management

Degree programme Transportation and Environmental Engineering

Major Water and Environmental Engineering **Code** R3005

Thesis supervisor Professor Harri Koivusalo

Thesis advisors D.Sc. Nora Sillanpää, M.Sc. Perttu Hyöty and M.Sc. Timo Nikulainen

Date 8.9.2017 **Number of pages** 39+2 **Language** English

Abstract

For quality management of stormwater and design of decentralized Low Impact Development (LID) systems, it is important to evaluate the source area contributions of stormwater pollutants. Monitoring of urban runoff quality requires extensive resources and thus modelling is often utilized. However, practitioners are often experienced in rainfall-runoff modelling, but the practical knowhow on water quality modelling is scarce. For this reason, this study was motivated by the need to assess stormwater quality modelling for establishing management practices. One objective was to assess stormwater quality modelling with literature based Event Mean Concentrations (EMC) for surface types and evaluate the relevance of different source areas in a typical spatial scale of a residential catchment (~10 ha). A second objective was to model decentralized filtration structures and evaluate their impacts on catchment scale runoff and pollutant loads.

A residential catchment of Vallikallio in Espoo, Finland, was modelled with US EPA Storm Water Management Model (SWMM). Rainfall, runoff and water quality data from the catchment outlet was utilized in the modelling and in the assessment of the results. Impermeable areas, such as parking areas, walkways, roads and roofs contributed the majority of the runoff volume and pollutant loads. The simulated pollutant loads were highly variable and the pollutant generation was impacted by weather conditions and source area characteristics, such as the contributing area and material.

Based on the source area modelling, LID management scenarios with bioretention cells and permeable pavements were formed. The LID scenarios on parking areas, roads and walkways reduced the amount of surface runoff and pollutant loads on a catchment scale to different extent, depending on the LID location and the pollutant considered. A combination of decentralized LIDs located on different impermeable source areas could be the most effective management option for targeting different pollutants.

Modelling stormwater quality with SWMM proved to be challenging, since the runoff and pollutant contributions of source areas were not directly obtainable and since the pollutant removal rates of the LIDs were not considered in SWMM. Analyzing the local rainfall and runoff distributions proved that in quality management and load reduction, the focus should be on intermediate sized storms. The EMC values used in this study can be utilized in modelling of similar catchments, as long as the uncertainties are recognized. Identifying the critical source areas and using long-term rainfall data when modelling pollutant loads is important for design of LIDs and management of stormwater quality.

Keywords Stormwater pollution, Event Mean Concentration, Low Impact Development, SWMM, Water Quality Modelling, Source Area

Aalto-yliopisto
Insinööritieteiden korkeakoulu

Aalto-yliopisto, PL 11000, 00076 AALTO
www.aalto.fi

Diplomityön tiivistelmä

Tekijä Camilla Tuomela

Työn nimi Huleveden kuormituslähteiden mallinnus osana hulevesien laadun hallintaa

Koulutusohjelma Yhdyskunta- ja ympäristötekniikka

Pääaine Vesi- ja ympäristötekniikka **Koodi** R3005

Työn valvoja Professori Harri Koivusalo

Työn ohjaajat TkT Nora Sillanpää, DI Perttu Hyöty ja DI Timo Nikulainen

Päivämäärä 8.9.2017 **Sivumäärä** 39+2 **Kieli** Englanti

Tiivistelmä

Hulevesien laadullisen hallinnan ja hajautettujen LID-rakenteiden (*Low Impact Development*) suunnittelussa on tärkeää tunnistaa hulevesien kuormituslähteet. Paljon resursseja vaativan hulevesien laadun monitoroinnin sijaan hyödynnetään usein veden laadun mallinnusta. Suunnittelijat ovat kokeneita sadannan ja valunnan mallintajia, mutta tietoa vedenlaadun mallintamisesta on vähän. Tästä syystä tätä tutkimusta motivoi tarve kehittää hulevesien laadun mallinnusta osana hallintamenetelmien kehittämistä. Työn tavoitteena oli tarkastella hulevesien laadun mallinnusta hyödyntäen kirjallisuuteen perustuvia huleveden keskimääräisiä pitoisuuksia (*Event Mean Concentration, EMC*) erilaisille pintatyypeille sekä arvioida eri kuormituslähteiden merkitystä asuinaluetason (~10 ha) hajakuormituksessa. Toisena tavoitteena oli mallintaa hajautettuja suodatusrakenteita sekä arvioida niiden vaikutuksia valuma-aluetason valuntaan ja kuormitukseen.

Työssä mallinnettiin espoolainen asuinalue Vallikallio US EPA SWMM-mallilla (*Storm Water Management Model*). Tulosten mallinnuksessa ja arvioinnissa hyödynnettiin valuma-alueelta kerättyä sadannan, valunnan ja vedenlaadun mittausaineistoa. Vettä läpäisemättömät alueet, kuten pysäköintialueet, kävelytiet, ajotiet ja katot, tuottivat valtaosan hulevesien valunnasta ja kuormituksesta. Mallinnetut kuormitukset vaihtelivat suuresti ja kuormituksen syntyyn vaikuttivat sääolosuhteet sekä kuormituslähteiden ominaispiirteet, kuten alueen koko ja materiaali.

Kuormituslähteiden mallinnustulosten pohjalta muodostettiin LID-hallintaskenaarioita biosuodatusrakenteilla ja läpäisevillä päällysteillä. Pysäköintialueille, ajoteille ja kävelyteille kohdennetut LID-skenaariot vähentivät valunnan määrää sekä kuormitusta valuma-aluetasolla eri suuruisesti, riippuen LID-rakenteen sijainnista ja haitta-aineesta. Eri LID-tekniikoiden yhdistelmät sijoitettuna läpäisemättömien pintojen yhteyteen voisi olla tehokkain hallintavaihtoehto erilaisten haitta-aineiden käsittelemiseksi.

Hulevesien laadun mallintaminen SWMM:llä osoittautui haastavaksi, sillä eri kuormituslähteiden osuutta valunnasta ja kuormituksesta ei ole suoraan saatavissa eikä SWMM huomioi haitta-aineiden pidättymistä LID-rakenteeseen. Paikallisen sadannan ja valunnan jakauman tarkastelu osoitti, että hulevesien laadun hallinnassa ja kuormituksen vähentämisessä tulisi keskittyä keskikokoisiin sadetapahtumiin. Tässä työssä käytettyjä EMC-arvoja voi hyödyntää vastaavien valuma-alueiden mallinnuksessa, kunhan epävarmuudet huomioidaan. Kriittisten kuormituslähteiden määrittäminen ja pitkäaikaisten sadanta-aineistojen käyttö mallintamisessa on tärkeää LID-rakenteiden suunnittelussa ja huleveden laadun hallinnassa.

Avainsanat Hulevesien kuormitus, Event Mean Concentration, Low Impact Development, SWMM, laadun mallinnus, kuormituslähde

Aalto-universitetet
Högskolan för ingenjörsvetenskaper

Aalto-universitetet, PB 11000, 00076 AALTO
www.aalto.fi

Sammandrag av diplomarbetet

Författare Camilla Tuomela

Titel Modellering av dagvattens föroreningskällor för hantering av dagvattenkvalitet

Utbildningsprogram Samhälls- och miljöteknik

Huvudämne Vatten- och miljöteknik **Kod** R3005

Övervakare Professor Harri Koivusalo

Handledare TkD Nora Sillanpää, DI Perttu Hyöty och DI Timo Nikulainen

Datum 8.9.2017 **Sidantal** 39+2 **Språk** Engelska

Sammandrag

För kvalitetshantering av dagvatten och planering av decentraliserade LID-system (*Low Impact Development*), är det viktigt att utvärdera belastningen från dagvattens föroreningskällor. Mätning av urban dagvattenkvalitet kräver omfattande resurser och därför används ofta modellering. Planerare har ofta erfarenhet av avrinningsmodellering, men lite erfarenhet av modellering av dagvattenkvalitet. Denna studie motiverades av behovet att undersöka modellering av dagvattenkvalitet för att utveckla praxis kring hantering av dagvattenkvalitet. Ett mål med studien var att undersöka modellering av dagvattenkvalitet med litteraturbaserade koncentrationer (*Event Mean Concentration, EMC*) för yttyper och att utvärdera relevansen av olika föroreningskällor i skalan av ett bostadsområde (~10 ha) . Ett annat mål var att modellera decentraliserade filtreringssystem och utvärdera deras inverkan på avrinning och föroreningsbelastning.

Bostadsområdet Vallikallio i Esbo, Finland, modellerades med US EPA SWMM (*Storm Water Management Model*). Nederbörds-, avrinnings- och vattenkvalitetsdata från avrinningsområdet användes i modelleringen och vid utvärdering av resultaten. Hårdgjorda ytor, som parkeringsplatser, gångvägar, bilvägar och tak bidrog till majoriteten av avrinningsvolymen och föroreningsbelastningen. Den simulerade föroreningsbelastningen varierade mycket och påverkades av väderförhållanden samt föroreningskällans egenskaper, så som den bidragande arean och materialet.

Baserat på modelleringen av föroreningskällor, bildades LID-scenarier med biofiltration och permeabla beläggningar. LID-scenarierna på parkeringsplatser, bilvägar och gångvägar minskade mängden avrinning och föroreningsbelastning i avrinningsområdet i olika utsträckning, beroende på LID-enheternas läge och det förorenande ämnet. En kombination av decentraliserade LID-enheter på olika hårdgjorda ytor kunde vara det mest effektiva alternativet för hantering av dagvattenkvalitet och specifika föroreningar.

Modellering av dagvattenkvalitet med SWMM visade sig vara utmanande, eftersom avrinning och föroreningsbelastning från olika föroreningskällor inte är direkt erhållbara från SWMM och eftersom LID-enheternas förmåga att avlägsna föroreningar inte beaktas i SWMM. Analyser av den lokala fördelningen av nederbörd och avrinning visade att vid hantering av dagvattenkvalitet och vid belastningsreduktion bör fokus läggas på mellanstora regn. De EMC-värden som användes i denna studie kan utnyttjas vid modellering av liknande avrinningsområden, så länge som osäkerheterna beaktas. Att identifiera de kritiska föroreningskällorna och att använda långtidsdata vid modellering av föroreningsbelastning är viktigt för dimensionering av LID-enheter och för hantering av dagvattenkvalitet.

Nyckelord Dagvattenförorening, Event Mean Concentration, Low Impact Development, SWMM, kvalitetsmodellering, föroreningskällor

Acknowledgements

This thesis was conducted at Aalto University School of Engineering as a part of the research project STORMFILTER. The research project was led by the Technical Research Centre of Finland Ltd (VTT) in cooperation with Aalto University and University of Helsinki. The project included 17 Finnish partners ranging from municipalities to material producers and designers.

The research project was jointly funded by the Finnish Funding Agency for Technology and Innovation (TEKES), industrial partners, VTT and Aalto University. Maa- ja vesitekniikan tuki ry (MVTT) provided additional funding for this thesis, for which I am very thankful.

I would first like to thank my supervisor Professor Harri Koivusalo at Aalto University and my instructors D.Sc. Nora Sillanpää from Aalto University, M.Sc. Perttu Hyöty and M.Sc. Timo Nikulainen from Sito, for valuable advice and comments throughout this process. I am especially grateful to Nora, for the knowledge she shared about stormwater and for the continuous guidance and support.

For the material used in this thesis, I would like to thank Helsinki Region Environmental Services Authority (HSY) for sewer network data from Vallikallio and Outi Raudaskoski for the original SWMM model made of Vallikallio.

I wish to thank the people I have met at the Water and Environmental Engineering Research Group at Aalto University, the water people at Sito and other people involved in the StormFilter project, for interesting discussions, meetings, and refreshing company during lunches and coffee breaks.

Finally, I wish to thank my friends for all the inspiration and sheering. I am grateful for the support and encouragement from my sisters and parents during my studies and thesis work. Jonathan, thank you for always believing in me and pushing me forward.

Espoo 8.9.2017

Camilla Tuomela

Table of contents

Abbreviations and symbols

APQ		Accumulative Pollutant Quantities
ARC		Accumulative Rain Count
ARQ		Accumulative Runoff Quantity
A_x		Area coverage
BMP		Best Management Practice
C_a	[mm]	Capacity
CDF		Cumulative probability Density Function
C_P	[g/l]	Pollutant concentration
C_R		Capture ratio
Cu		Copper
C_{VOL}		Volumetric runoff coefficient
D	[mm]	Distance from drain to surface layer
EIA		Effective Impervious Area
EMC		Event Mean Concentration
LID		Low Impact Development
L_S	[g]	Subcatchment load
MRL		Land Use and Building Act (132/1999)
n		Flow exponent
Pb		Lead
q	[mm/h]	Flow coefficient
R	[l]	Runoff
R_n	[l]	New runoff
R_{on}	[l]	Runon
SMC		Site Mean Concentration
SWMM		Storm Water Management Model
T	[h]	Drain time
TIA		Total Impervious Area
TN		Total Nitrogen
TP		Total Phosphorus
TSS		Total Suspended Solids
US EPA		United States Environmental Protection Agency
V_{TS}	[mm]	Total storage volume
W	[g]	Pollutant washoff load
Zn		Zinc

List of figures

List of tables

1 Introduction

1.1 Background to stormwater management

Urbanization and changes in land use have altered the hydrology in urban environments. The impacts of these changes are seen as an increase in runoff volumes, higher peak flows, and a decrease of the baseflow (Burns *et al*. 2012). Urbanization also affects urban streams, with the manipulation of channels, altered stream geomorphology, changes in water chemistry, an increase of water temperature and light, the loss of habitats and reduction of habitat complexity (Wenger *et al*. 2009).

Urban areas feature various impervious surfaces, such as roads, walkways, parking areas, roofs and compact soil, and thus imperviousness is an important characteristic regarding urbanization and its impacts on urban runoff (Leopold 1968; Lee & Heaney 2003). Impervious surfaces are the main contributors of urban surface runoff, but also pervious surfaces can generate runoff at larger amount of rainfall. Different land use and surface types function as source areas for stormwater runoff and associated pollutants.

With an increased amount of urban stormwater, there is an increased risk for urban floods (Burns *et al.* 2012). A traditional approach to stormwater management is the construction of efficient drainage systems that rapidly route the stormwater to receiving waterways. Impervious source areas are usually connected directly to sewers and runoff is thus conveyed with little or no treatment or attenuation (Burns *et al.* 2012). Stormwater carries contaminants from diverse sources and can pollute the environment and receiving waters.

1.2 Stormwater quality and pollutants

Urban runoff is a diffuse pollution source with numerous sources of pollutants. Major sources of contaminants are construction sites, traffic, litter, animal feces, vegetation residues, erosion, and atmospheric deposition, as well as overflow from combined sewers (Burton & Pitt 2002; Rossman & Huber 2016b). Urban pollution problems can be divided into two groups based on their impact: acute and cumulative (Harremoës 1988). High pollutant loads or concentrations in the receiving water cause acute problems, while long-term gradual build-up and accumulation of nutrients and metals cause cumulative problems. Typical contaminants in urban stormwater runoff are sediment and floatables, pesticides and herbicides, organic materials, nutrients, metals, oil and grease, bacteria and viruses (Rossman & Huber 2016b). The most common pollutants are according to Roesner *et al.* (2001) total suspended solids (TSS), the nutrients phosphorus (P) and nitrogen (N), the heavy metals copper (Cu), lead (Pb) and zinc (Zn), and bacteria from feces.

The concentrations of pollutants may be significant for receiving waters (Rossman & Huber 2016b), but owing to a chronic nature of most pollution problems in urban receiving waters, also the total pollutant loads carried by runoff are important. With larger storms, the total pollutant load increases, but the pollutant concentration is diluted (Sillanpää & Koivusalo 2015). Smaller storms generate smaller pollutant loads, but with higher pollutant concentrations.

Urban catchments contain a variety of different source areas, both permeable and impermeable, that produce runoff and pollutants with varying extents. The pollutant contributions vary between source areas and with weather conditions. Waschbusch *et al.* (1999) monitored residential areas in Madison, Wisconsin and reported that streets were the largest contributions of solids, while lawns of phosphorus loads. According to Petrucci *et al.* (2014), roofs in urban areas are a main source of lead and an important source of zinc. According to Pitt *et al.* (2004), traffic-related areas contribute most of the particulate pollutants during small low-intensity rains, but during larger storms, the soil surface becomes an important contributor of particulate pollutants. Studies in Finland (Sillanpää & Koivusalo 2014; Guan *et al.* 2016) have indicated that there is an increase of runoff from pervious surfaces when a storm depth of 17-20 mm is exceeded. Pervious areas are thus likely to contribute with pollutants also in Finland.

1.3 Stormwater quality management

Knowledge about stormwater pollution has led to stormwater management objectives with an aim to reduce pollutant loads and control source areas (Burns *et al.* 2012; Petrucci *et al.* 2014). Different sustainable treatment strategies have been developed and various terms are used for them, as Low Impact Development (LID), Best Management Practices (BMP) and Sustainable Urban Drainage Systems (SUDS). LID refers to stormwater management with focus on capturing and retaining stormwater runoff at the source, with small-scale treatment units and decentralized systems. Reducing runoff quantity at the source area, by e.g. increased infiltration or temporary storage also improves the water quality (Huber *et al.* 2006). By storing and detaining runoff, LID can reduce the negative impacts of urban development on the hydrological cycle and pollutant loads (Burns *et al.* 2012). There are many different types of LID practices, also referred to as LID controls, such as permeable pavements, street planters, swales and different filtration structures, to name a few. LID controls usually consist of different combinations of layers, such as vegetation, engineered soil, sand, gravel, coarse aggregates or synthetic drainage mats.

There are several factors affecting stormwater management, including geophysical factors, such as climate, hydrology, soil and topography, technical and economic factors, as well as both social factors and legislation (Barbosa *et al.* 2012). The stormwater management in Finland is mainly regulated in Chapter 13a of the Land Use and Building Act (MRL) (132/1999). The 13a Chapter was added to MRL in 2014 setting the general objectives of stormwater management. The infiltration, detention and treatment of stormwater at the source should be promoted, instead of discharging untreated stormwater into watercourses. In Finland, the municipalities are responsible for stormwater management in street plan areas and some municipalities have developed stormwater strategies and plans. In Finland stormwater management have focused on quantity management, there are not any legal constraints or regulations for stormwater quality and thus few established practices for designing stormwater quality management. However, over the past few years one design practice for stormwater management controls has become common, where one m^3 storage volume is allocated for each 100 m^2 of impermeable surface (Raudaskoski 2016). This design practice originates from a traditional 10-minute drainage design storm that corresponds to approximately 10 mm rainfall in local conditions. The storage volume is thus not based on a detailed analysis of long-term rainfall.

Although there is increased knowledge about stormwater pollution and about the development of new sustainable treatment strategies and LID controls, the shift towards them has been slow (Elliott & Trowsdale 2007). By the use of effective modelling tools, LID design and application could be more efficient and the results could be used for the development of policies (Elliott & Trowsdale 2007).

1.4 Stormwater quality modelling

Petrucci *et al.* (2014) listed three main modelling approaches in current urban hydrology studies: flow-rate modelling, quality modelling and integrated modelling. The classical approach is flow-rate modelling of urban watersheds and drainage systems, which can be done with many distributed and detailed models, as Storm Water Management Model (SWMM) (Rossman 2015) and MIKE URBAN. The quality modelling approach focuses on modelling the urban flows of pollutants and is important when assessing impacts on waterways downstream of the catchment. The integrated modelling approach is not yet a common practice, but attempts to couple several models into complex systems of sewer networks and receiving waterways.

The monitoring of urban runoff quality requires extensive resources. Thus, modelling is used as a tool for prediction, analysis and management of urban water quality and pollution (Zhu *et al*. 2012). The U.S. EPA SWMM software is widely used for simulating urban runoff and can be used to simulate water quality. The most common method for estimating nonpoint pollutant loads is by the use of constant Event Mean Concentrations (EMC) for pollutants (Rossman & Huber 2016b). EMCs for pollutants are typically determined based on flow-weighted water quality sampling and laboratory analysis and they can be found in literature for different source areas and pollutants. EMCs are often the only values available and are hence used in stormwater quality modelling (Rossman & Huber 2016b).

The performance and abilities of ten stormwater models were evaluated by Elliott and Trowsdale (2007) and they concluded that improvement is still needed regarding modelling of water quality and LID applications. One limit of current urban modelling is that even though the models have large possibilities, also for quality modelling, they are often used in a narrow way (Petrucci *et al*. 2014). Compared with flow-rate models, water quality models are yet seen to have smaller reliability, due to lack of data, measurement uncertainties, questions related to physical and chemical processes and lack of modelling experience (Petrucci *et al*. 2014).

1.5 Rain events in stormwater modelling and management

The focus of urban stormwater management and modelling on peak flow rates and events as well as catchment behavior during extreme rain events is important regarding floods, but unsatisfactory regarding water quality and management effects on receiving waters (Petrucci *et al.* 2014). The use of simple design storms when designing drainage systems is a too straightforward approach when complex water quality problems are being addressed (Pitt 1999). Small rain events are frequent and produce runoff that might be hydraulically negligible, but are relevant when considering pollutants and stormwater quality (Petrucci *et al.* 2014). Pitt (1999) concluded that a wide range of different types of rain events should be considered when designing urban drainage systems and hence design practices based on a single design storm cannot produce reliable solutions for all urban runoff management targets.

Pitt (1999) evaluated monitored rainfall and simulated runoff distributions for 24 different locations in the U.S. and divided the rainfall distributions into three different categories, with different management approaches for each. The categories were determined by long-term continuous simulations with the Source Loading and Management Model (SLAMM). The rain depths defining each category varied and were dependent on local measurements and conditions. The first category included frequent small rains accounting for 50-70% of the rain events, but only produced 10-20% of total runoff volume. The pollutant discharges were relatively low, but the high concentrations might be critical for receiving waterways. The second category included intermediate rains accounting for 30-50% of the rain events, but produced 75-90% of total runoff volume. These storms were responsible for the largest part of the pollutant discharges and long-term loads. The third category included large infrequent rain events that are associated with drainage design. The large rains are associated with a few percent of the annual rain events, and produced about 10% of total runoff volume and pollutant discharges. When analyzing urban runoff, also smaller rains are very important since they account for large parts of the annual runoff volume compared with rarer flooding events and contribute a majority of the pollutant loads (Pitt 1999).

For a more effective stormwater drainage design, rainfall and runoff probability distributions can be used (Pitt 1999). Pitt (1999) plotted Cumulative probability Density Functions (CDFs) of rainfall, runoff and pollutant distributions. Rainfall was expressed as Accumulative Rain Count (ARC), runoff as Accumulative Runoff Quantity (ARQ) for both residential and commercial areas, and Accumulative Pollutant Quantity (APQ). From CDFs generated with local data, it can be seen which rain depths are producing most of the runoff and pollutant loads in the studied catchment.

1.6 Research objectives

This thesis aims to model and assess stormwater filtration structures in a densely constructed residential catchment and their impact on runoff and pollution reduction in an urban catchment scale. This thesis is motivated by the need to develop stormwater quality management. The review of existing literature and practice demonstrates that current stormwater management focuses on quantity management and that stormwater quality modelling has to be utilized for establishing stormwater quality practices. Information about source areas is needed for understanding the impacts of urbanization on urban runoff and diffuse pollution, and for outlining a cost-effective design and location prioritization of decentralized LID controls. The methodological approach of this thesis is to use available experimental results from a local Finnish catchment and numerical modelling. The analysis is limited to the residential catchment Vallikallio, selected stormwater pollutants and specific filtration structures.

The specific tasks and objectives of the study are to:

1) Simulate pollutant loads of stormwater with US EPA SWMM to determine source area contributions within an urban catchment.
    a. Evaluate how applicable it is to use literature EMC values for stormwater quality modelling.
    b. Evaluate the impacts and importance of different types of source areas on the generation of pollutant loads.

2) Model LID management scenarios with focus on filtration structures.
    a. Evaluate the effect of the scenarios and filtration structures on catchment-scale pollutant loads, to determine where it is cost-effective to locate LID controls.

3) Determine rainfall, runoff and pollutant distributions and rain categories for stormwater quality management.

2 Materials and methods

2.1 Description of study site Vallikallio

The study site Vallikallio is a residential area located in Espoo in southern Finland (Figure 1). In Vallikallio, the landscape is characterized by three and four storey apartment buildings, asphalted roads, walkways and parking areas, as well as vegetated areas. The oldest buildings were built during the 1970s and the newer during the 1990s. The vegetated areas are natural pine forests as well as lawns, shrubs and plants. There are also areas with sand or gravel scattered around the catchment, mostly consisting of dirt walks or playgrounds. Within the yards, also some stone or tile-paved areas can be found, as well as one larger paved walking area.

Figure 1. Location of the study site Vallikallio in Espoo, southern Finland (modified from the Cities of Espoo, Helsinki and Vantaa 2017).

The total area of the studied site is around 11 hectares, of which 53% consists of impermeable surface types, of these impermeable areas 34% are asphalt covered and 19% are roofs. The surface types and respective areas in the Vallikallio catchment can be seen in Table 1. The soil within the area consists mostly of sandy till. Open bedrock is also partly visible around the area. In some areas, there is only a thin sandy till layer on top of the bedrock.

Table 1. Land use in Vallikallio and their respective areas in hectares and as percent of the whole catchment area.

Land Use	Area (ha)	Area (%)
Parking areas	1.6	14
Paved walkways	1.6	14
Roads	0.7	6
Roofs	2.1	19
Open rock	0.04	0.4
Stone or tile paving	0.2	2
Sand or gravel	0.7	6
Vegetation, lawns	4.3	38

Vallikallio is a part of the Monikonpuro brook catchment. In Vallikallio, stormwater is discharged to a subsurface pipe sewer network. The pipe sewer network covers the whole catchment area and is mostly located under the largest roads. The majority of rooftops and areas related to traffic are directly connected to the sewer network. The sewer network in Vallikallio connects to an open ditch and further to Monikonpuro brook. More information about the catchment and previous studies can be found in Sillanpää (2013).

2.2 Monitoring data from Vallikallio

The Vallikallio catchment has been studied at the Helsinki University of Technology and Aalto University in different research projects since 2001 (Aaltonen 2008; Sillanpää 2013; Raudaskoski 2016). Precipitation, water depth in the sewer network and water quality has been monitored at the catchment outlet from 2001 to 2006. From 2001 to 2004, the discharge at the catchment outlet was recorded every 10 minutes and from September 2005 to 2006, every two minutes. Precipitation was monitored with a rain gauge located at a building roof five meters above ground. Rainfall intensity was logged as ten-minute or two-minute precipitation sums. Water depth was monitored with a pressure transducer located in a manhole of the sewer network. Sillanpää (2013) calculated the flow rate using an empirically determined stage-discharge calibration curve.

Water quality was monitored with automatic samplers as flow-weighted sampling. The samples were analyzed at a laboratory for total suspended solids, total phosphorus (TP) and total nitrogen (TN) amongst other quality parameters. From the laboratory results, Sillanpää (2013) calculated long-term pollutant loads and event-scale water quality parameters as EMCs, Site Mean Concentrations (SMC) and event mass loads.

In this study, data from the summer months (June to August) of 2005 and 2006 were used in the simulations of the source area contributions of stormwater pollutants. These two summers were very different regarding the amount of precipitation (Table 2). Summer of 2005 was a rainy summer while the summer of 2006 was dry with little precipitation. Data from June to August of 2003 were added to the simulation of LID controls, to represent a summer with average precipitation.

Table 2. Precipitation during summers of 2003, 2005 and 2006.

Period	Precipitation (mm)
1.6-31.8.2003	180
1.6-31.8.2005	348
1.6-31.8.2006	52

2.3 Surface type specific Event Mean Concentrations

For urban runoff, pollutant concentrations are typically represented as EMCs, which are defined per storm event as the ratio of total pollutant load to event runoff volume. In this study, surface type specific EMC values were obtained from literature for TSS, TP, TN, Pb, Cu and Zn for surface types listed in Table 1.

Since the literature-based values were very diverse, the EMC values were combined into three to five different sets for each pollutant. One EMC set included literature values for each surface type. In total 23 EMC sets were obtained for the six studied pollutants (Table *3*). Fewer EMC sets were simulated for the metals, because of difficulty of finding literature values. Each set had an EMC value for respective surface type. The division into surface types is different among the references, as well as the pollutants studied. In some sets, the EMC values are from the same reference and in other sets, values from different references were combined to provide a full set with values for all studied surface types. Median EMC values were preferred but in some references, only mean EMC values were available. In a few references, only total Kjeldahl nitrogen was available, but total nitrogen was preferred. The specific EMC values used for each surface type in the different sets can be found in Appendix 1

Table 3. Sets of EMC values for each selected stormwater pollutant and the references for literature values in each EMC set.

Pollutant	EMC sets from literature					References
TSS	EMC 1 [e]	EMC 2 [e,b]	EMC 3 [c,d]	EMC 4 [a,c]	EMC 5 [c,g]	a) Bannerman et al. (1993)
TP	EMC 6 [e]	EMC 7 [c,e]	EMC 8 [b,c,e]	EMC 9 [f]	EMC 10 [a,f]	b) Duncan (1999)
TN	EMC 11 [e]	EMC 12 [b,c,e]	EMC 13 [f]	EMC 14 [d]		c) Gilbert & Clausen (2006) d) Göbel et al. (2007)
Pb	EMC 15 [e]	EMC 16 [d]	EMC 17 [a]			e) Heaney et al. (1999)
Cu	EMC 18 [e]	EMC 19 [d]	EMC 20 [a]			f) Pitt & McLean (1986)
Zn	EMC 21 [e]	EMC 22 [d]	EMC 23 [f]			g) Waschbusch et al. (1999)

2.4 Storm Water Management Model of Vallikallio

SWMM has widely been used for simulating stormwater in urban environments (Rossman 2015). SWMM is a dynamic simulation model that can be used for simulating water runoff quantity and quality for long-term or single events. This study was built on an existing SWMM 5.0 model of Vallikallio, previously made by Raudaskoski (2016). The model calibration was conducted by Raudaskoski (2016) using monitoring data from six storms, three events for both model calibration and validation. In general, the calibrated model simulated events rather well with the R^2 values ranging from 0.75 to 0.94 for the six events. It is noteworthy that the model tended to underestimate the peak flow rates. More details about the model calibration are presented in Raudaskoski (2016).

In SWMM, a catchment is divided into subcatchment areas that can be connected to each other, a sewer network or a channel. The subcatchments receive water as precipitation and as runon from other connected subcatchments and generate runoff and pollutant loads. The subcatchment connections in the model defines how runoff is routed between the subcatchments and further to the sewer network. In the model, the catchment of Vallikallio was divided into 610 different subcatchments. Each subcatchment represents one source area and has one assigned land use type. Figure 2 is an illustration of the model, with subcatchments, the sewer network and the catchment outlet.

Figure 2. SWMM model of Vallikallio, with surface types as subcatchments, the sewer network and catchment outlet (modified from Raudaskoski 2016).

The SWMM model by Raudaskoski (2016) was originally used for modelling stormwater quantity. In this study, the model was used to simulate both water quantity and quality in Vallikallio. Some small changes were made to the model based on field investigations on the site as well as aerial photos. The asphalted areas in the model were further divided into parking areas, paved walkways and roads. The surface types for a few other subcatchments were changed and some of the routing paths between subcatchments and connections to the sewer network were updated. Subcatchment parameters calibrated by Raudaskoski (2016) were used (Table 4).

Table 4. Source areas and SWMM parameters calibrated by Raudaskoski (2016).

Source areas	Imperviousness (%)	Manning's roughness (-)	Depression storage (mm)
Parking areas	94.1	0.016	0.826
Paved walkways	94.1	0.016	0.826
Roads	94.1	0.016	0.826
Roofs	100	0.0084	0.28
Open rock	100	0.05	3.16
Stone or tile paving	84.9	0.019	0.30
Sand or gravel	33.0	0.01	0.40
Vegetation, lawns	0	0.50	2.45

In the SWMM application of this study, the Dynamic wave was used to describe the runoff routing in the stormwater sewer network and the Green-Ampt method to describe the surface infiltration of water (Rossman 2015).

The soil types in Vallikallio were set and assigned the values presented in Table 5. In the beginning, the soil type was defined as Sandy clay loam while modelling the source area loads. When the LID controls were modeled, the soil was changed to Silty Cay loam. The soil type was changed to lower the hydraulic conductivity of the soil to prevent too high infiltration during the LID modelling.

Table 5. Soil types in the model and assigned soil parameters from Guan et al. (2016).

Soil type	Saturated hydraulic conductivity (mm/h)	Suction head (mm)	Initial soil moisture deficit (-)
Sandy clay loam	1.524	219.964	0.154
Silty clay loam	1.016	270.002	0.129

2.4.1 Modelling steps and parameters

In SWMM, a typical urban drainage system is divided into four major compartments, which are the atmosphere, land surface, groundwater and transport (Rossman 2015). Water and material flow in different forms between these compartments. The SWMM processes modelled in this study were rainfall and runoff, flow routing and water quality, both without and with LID Controls. The hydrological processes and steps modelled with SWMM are illustrated in Figure 3.

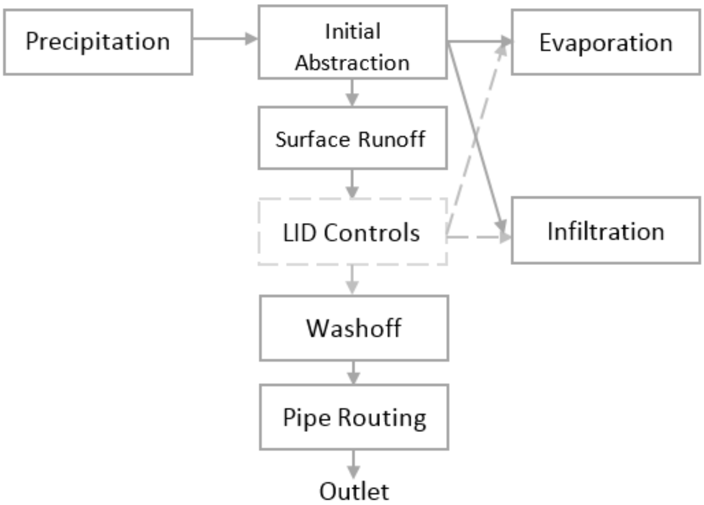

Figure 3. Steps and hydrological processes modelled in SWMM.

First, the source area contributions of pollutants were simulated for the Vallikallio catchment, without any specific stormwater management other than the existing sewer system. To be able to simulate water quality, pollutant objects were added to the SWMM model and EMCs were assigned for each pollutant to each land use type. Pollutant washoff was simulated with each EMC set in Table 3. No pollutant buildup or street cleaning was defined or simulated.

Runoff from subcatchments can contain pollutants from direct rainfall and from runon originating from upstream subcatchments. The concentration of pollutants in precipitation was assigned to zero, considering the use of literature based EMCs. The literature EMCs are usually based on site monitoring, and thus the deposition is taken into account in the stormwater pollutant EMCs.

Based on the simulated source area contributions, different types of LID controls were added into the model. The simulated LID controls were bioretention cells and permeable pavements. Bioretention cells and permeable pavements were separately simulated for all asphalted areas in the model, including parking areas, roads and walkways.

The LID controls in SWMM have vertical layers, which have specific properties (Figure 4) and parameters assigned the values listed Table 6. In the current study, underdrains were used in both LID types as is often recommended for cold climate conditions and soils with low permeability. Infiltration from the structures into the soil was permitted.

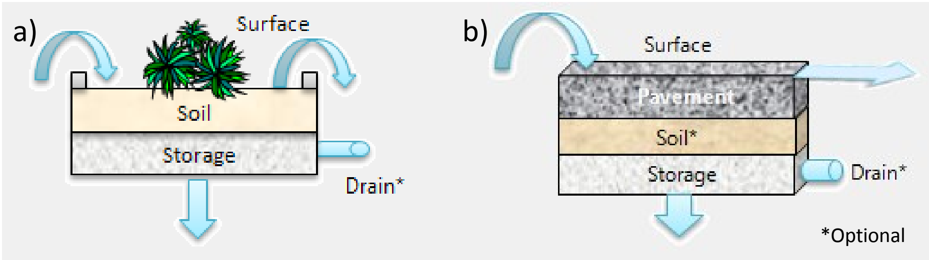

Figure 4. Illustration of two SWMM LID controls: bioretention cell (a) and permeable pavement (b) with vertical layer structures (modified from US EPA SWMM 5.1 user interface).

The LID parameters and layer properties (Table 6) were decided based on literature and discussions with the steering group (SFTSG 2017) about the current design practice in Finland. The soil layer parameter values for the bioretention cell present the characteristics of a typical engineered soil (Rossman & Huber 2016b). The soil layer parameter values for the permeable pavement represent sand (Rossman & Huber 2016a).

The flow coefficient of the underdrain layer was calculated by the following equation:

$$q = \frac{2D^n}{T}, \tag{1}$$

where q (mm/h) is the flow coefficient, D (mm) is the distance from the drain to the surface layer including the berm height, n (-) is the flow exponent and T (h) is the drain time. The drain times of the drain layer were assigned to be 12 h for bioretention cells and 2 h for permeable pavements.

Table 6. LID controls modelled in Vallikallio SWMM application and the assigned layers and parameter values.

LID layers	Parameter	Bioretention cell	Permeable pavement
Surface layer	Berm height (mm)	200	0
	Vegetation volume fraction	0.15	0
	Surface roughness (Manning's n)	0.6	0.2
	Surface slope (percent)	0.5	*
Soil layer	Thickness (mm)	700	400
	Porosity (volume fraction)	0.52 (b	0.463 (a
	Field capacity (volume fraction)	0.15 (b	0.094 (a
	Wilting point (volume fraction)	0.08 (b	0.05 (a
	Conductivity (mm/h)	119.4 (b	114.0 (a
	Conductivity Slope	39.3 (b	48 (a
	Suction head (mm)	48.26 (b	49.53 (a
Storage layer	Thickness (mm)	300	300
	Void ratio (voids/solids)	0.5	0.43 (a
	Seepage rate (mm/h)	1.016 (c	1.016 (c
	Clogging factor	0	0
Drain layer	Flow coefficient (mm/h)	5.4	25
	Flow exponent	0.5 (a	0.5 (a
	Offset height (mm)	150	150
Pavement layer	Thickness (mm)		75
	Void ratio (voids/solids)		0.24
	Impervious surface fraction		0
	Permeability (mm/h)		360 (d
	Clogging factor		0

*Same as the specific subcatchment
References: a) Rossman & Huber (2016a)
b) Rossman & Huber (2016b)
c) Guan *et al.* (2016)
d) Kling *et al.* (2015)

For bioretention cells, the area coverage was defined to be 5% of the specific subcatchment area. For permeable pavements, the area, width and slope of the pavement layer were set equal to the same characteristics of the subcatchment area. Thus, the LID structures in different subcatchments had some catchment specific parameter values.

The capacity of LID structures can be calculated based on the parameters and properties, by calculating the capture ratio and total storage volume of the structure (Table 7) (Rossman & Huber 2016b). First, the capture ratio of the structure is calculated based on the area coverage, which is 0.05 for bioretention cells and 1.0 for permeable pavements:

$$C_R = \frac{1-A_x}{A_x}, \tag{2}$$

where C_R (-) is the capture ratio and A_x (-) is the area coverage.

Secondly, the total storage volume contained in the LID structure is calculated. The total storage volume is the sum of the structures layers thicknesses multiplied with the void ratios. With the capture ratio and total storage volume, the LID structures capacity can be calculated as follows:

$$C_a = \frac{V_{TS}}{(C_R+1)}, \tag{3}$$

where C_a (mm) is the capacity, V_{TS} (mm) the total storage volume and C_R (-) is the capture ratio.

Table 7. Calculated capture ratio, total storage volume and capacity for the modelled LID structures.

	Bioretention	**Permeable pavement**
Capture ratio C_R (-)	19	0
Total storage volume V_{TS} (mm)	658	312
Capacity C_a (mm)	33	312

2.5 Calculating source area loads

The source area loads for stormwater pollutants were calculated based on the water quality simulations. The calculations were done in a spreadsheet program since there is no alternative for directly obtaining washoff per source area from the simulation results in SWMM. The simulation results for runoff and pollutant washoff from each subcatchment were obtained and further analyzed.

The pollutant concentration C_P (g/l) was calculated based on the simulated subcatchment pollutant washoff load W (g) and runoff R (l):

$$C_P = \frac{W}{R} \tag{4}$$

To be able to consider only the load generated in a specific source area, the runon from other directly connected subcatchments were subtracted from the subcatchment runoff. In some subcatchments, especially permeable vegetated areas, runon was larger than runoff due to infiltration. In these cases, the runon was not subtracted and a new runoff was calculated as following:

$$\begin{cases} R_n = R - R_{on}, & R_{on} \le R \\ R_n = R, & R_{on} > R \end{cases}, \tag{5}$$

where R_n (l) is new runoff, R (l) is runoff and R_{on} (l) is runon.

A new pollutant load was calculated for each subcatchment, by multiplying the concentration with the recalculated runoff:

$$L_S = C_P R_n, \quad (6)$$

where L_S (g) is the subcatchment load, C_P (g/l) is pollutant concentration and R_n (l) is new runoff.

The subcatchments were grouped based on the surface type and the pollutant load and total runoff was summed for each source area type. From the source area loads, the load distribution between the different source areas was calculated. The total catchment load was calculated from the cumulative source area loads, and further SMC was calculated by dividing the total load with the total simulated runoff at the catchment outlet.

After simulating subcatchment runoff and washoff and calculating the source area loads and distributions, the performance of the EMC sets was analyzed and compared with monitoring data. There were no monitoring data available for source area loads, but pollutant loads and SMCs based on monitoring from the catchment outlet. The measured catchment outlet load was recalculated by dividing the monitored SMC with simulated catchment runoff. Monitored quality data from Vallikallio was available for TSS, TP and TN (Sillanpää 2013). Valtanen *et al.* (2014) have studied stormwater pollutant loads and concentrations in Lahti, and since there was no monitored data of metal concentrations in Vallikallio, the EMCs for Pb, Cu and Zn from Ainonpolku catchment in Lahti were multiplied with the runoff from Vallikallio to estimate loads comparable with the simulation results.

The pollutant loads simulated with different EMC sets were evaluated by first comparing the SMC for each set with the monitored SMCs from Vallikallio and Lahti. An accepted difference was ± 50% between the simulated and monitored values. Second, the simulated and calculated total catchment loads were compared with the monitored loads. Finally the source area pollutant distribution and original EMC values were evaluated, to see how realistic they were and if there were differences in the distributions between different sets of the same pollutant. Based on these criteria, one set of EMC values was chosen for further simulations of LID controls.

2.6 Calculating pollutant reduction

Based on the LID control simulations, runoff and pollutant reductions were compared with the results from the original model scenario without LID controls. SWMM only models the reduced runoff flow volume and runoff mass load and not the pollutant reduction that the LID control itself could provide (Rossman 2015). Thus, the pollutant loads from the different LID scenarios were recalculated in a spreadsheet program with a removal rate for each pollutant and the loads originating from the source area where the LID was located. The removal rates (Table 8) for each pollutant were obtained from literature (Field & Sullivan 2003) for TSS and TN, and for TP, Cu, Pb and Zn from StormFilter laboratory material tests conducted by VTT (2017). The removal rates from VTT tests were calculated as an average for the different materials tested.

Table 8. Pollutant removal rates for pervious pavements and bioretention structures.

Pollutant	Suspended solids	Phosphorus	Nitrogen	Lead	Copper	Zinc
Removal rate (%)	95 (a	97 (b	85 (a	95 (b	88 (b	91(b

References: a) Field & Sullivan (2003), b) VTT (2017)

2.7 Defining rainfall, runoff and pollutant distributions

Rainfall, runoff and pollutant distributions for Vallikallio were defined with CDFs, in a similar way as Pitt (1999). Monitored rainfall, simulated daily runoff and pollutant loads from the summers (June-August) of 2003, 2005 and 2006 were used. The rainfall data was organized in order of magnitude, from the smallest to the largest rainfall. Days with rainfall less than 0.4 mm were eliminated. ARC was calculated based on the number of days with rainfall and expressed in percent. ARQ was calculated based on cumulative runoff volume and expressed in percentage value. Both ARC and ARQ were plotted against daily rain depth on a logarithmic scale. APQs were calculated based on cumulative daily pollutant loads for each pollutant and plotted against rain depth.

Runoff distributions were also plotted for four different urban land use types (Table 9) based on total impervious area and runoff coefficients. The runoff coefficient is the relationship between rainfall and runoff. Large and small rains should be expressed with different coefficients since they produce runoff to a different extent. For small and moderate storms less than 18 mm a regression equation (Sillanpää & Koivusalo 2014) was used to estimate an average runoff coefficient and further the runoff:

$$C_{VOL} = 0.8334(TIA)^2 - 0.0139(TIA) + 0.0607, \quad (7)$$

where C_{VOL} (-) is the volumetric runoff coefficient and TIA (-) the total impervious area.

For storms larger than 18 mm, the runoff was calculated directly using larger runoff coefficients suggested for sewer design (Table 9). Based on the estimated runoff depths, ARQ was calculated for each catchment type and plotted against rain depth.

Table 9. Catchment types and their TIAs and runoff coefficients used for calculating runoff and analyzing runoff distributions.

Catchment type	TIA	Runoff coefficient (Karttunen 2004)
Low-density residential area	0.2	0.25
High-density residential area	0.5	0.6
Very high-density residential area	0.7	0.7
City-center or commercial area	0.9	0.9

2.7.1 Determining rain categories

Based on the rainfall and runoff distributions, the rainfall distributions were divided into three different categories, small, intermediate and large rains (Pitt 1999). Pitt (1999) presented boundaries for the percent of rain events and runoff produced within each category. Each category is defined by a range of rain depth, which was determined for Vallikallio by using the classification presented by Pitt (1999) as a guideline and analyzing the distribution and characteristics of each category (Table 10).

Table 10. Characteristics and percentage ranges used for determining rain categories (Pitt 1999) for Vallikallio.

Category	Small rains	Intermediate rains	Large rains
Percent of rain events (%)	50-70	30-50	1-5
Percent of runoff produced (%)	10-20	75-90	10

3 Results

3.1 EMC values in stormwater quality modelling

The total pollutant loads were simulated for TSS, TP, TN, Pb, Cu and Zn and were compared with measured loads (Figure 5). For TSS, TP and TN measurements were available from the Vallikallio catchment. There were no measurements from the site for the simulated metals Pb, Cu and Zn, so the metal loads were compared with measurements from a residential catchment in Lahti, Finland (Valtanen *et al.* 2014).

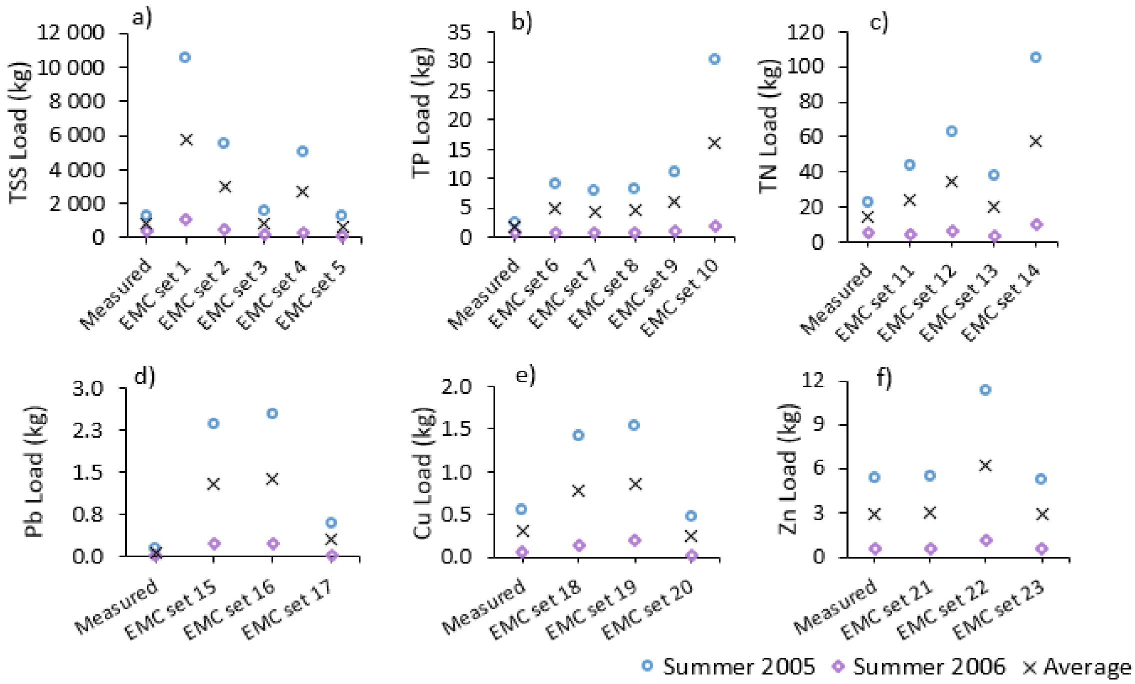

Figure 5. TSS (a), TP (b), TN (c), Pb (d), Cu (e) and Zn (f) pollutant loads for summers of 2005 and 2006, simulated with different EMC sets from literature and compared with measured loads from Vallikallio and Lahti (Valtanen et al. 2014). Descriptions of the literature references for the EMC sets 1-23 are given in Section 2.3.

The simulations with different EMC sets produced variable pollutant loads (Figure 5). The range of pollutant loads between the two summers was larger for the simulated loads, than for the measured loads. The rainy summer 2005 produced about 19000 m^3 runoff and large pollutant loads, while the dry summer 2006 produced about 1900 m^3 runoff and smaller pollutant loads that were closer to the measured values. For the measured loads, the rainy summer produced loads from two to nine times larger than the dry summer 2006. For the simulated loads, the rainy summer produced loads from nine to 21 times larger than the dry summer.

The washoff loads of TSS (Figure 5a) had a large range with big differences between the simulations. A few simulations estimated loads similar to, or even smaller (–20-80%) than the measured TSS loads for the dry summer. Some simulations yielded TSS loads three to seven times larger than the measured load for the rainy summer. The washoff loads of TP (Figure 5b) were similar for four simulations, the loads for the dry summer were close to the measured (+0-31%), while the loads for the rainy summer were two to three times larger than the measured. One simulation yielded a TP load eleven times larger than the measured load for the rainy summer. The washoff loads of TN (Figure 5c) varied between the simulations. For three simulations, the TN loads were ±20-30% of the measured loads during the dry summer and 60-180% of the measured loads during the rainy summer. One simulation yielded a TN load four times larger than the measured during the rainy summer.

The washoff loads of Pb (Figure 5d) were 16 to 18 times larger than the measured load for two simulations while one simulation produced loads 150% larger than the measured for the dry summer and four times larger than the measured for the rainy summer.
The washoff loads of Cu (Figure 5e) were 150-250% larger than the measured loads for two simulations while 20-60% smaller for one simulation. The washoff loads of Zn (Figure 5f) were very similar (+0-10%) to the measured values for two simulations while one simulation produced loads around 110% larger than the measured for both summers.

An estimate of SMC was calculated for each pollutant from the runoff and loads simulated with each EMC set for summers 2005 and 2006. The calculated SMCs were compared with measured SMCs (Figure 6) from Vallikallio and Lahti (Valtanen et al. 2014). For the measured SMCs from Lahti (Figure 6d-f) there is only one value, while for the measured SMCs from Vallikallio (Figure 6a-c) there are values for both summers and an average of them.

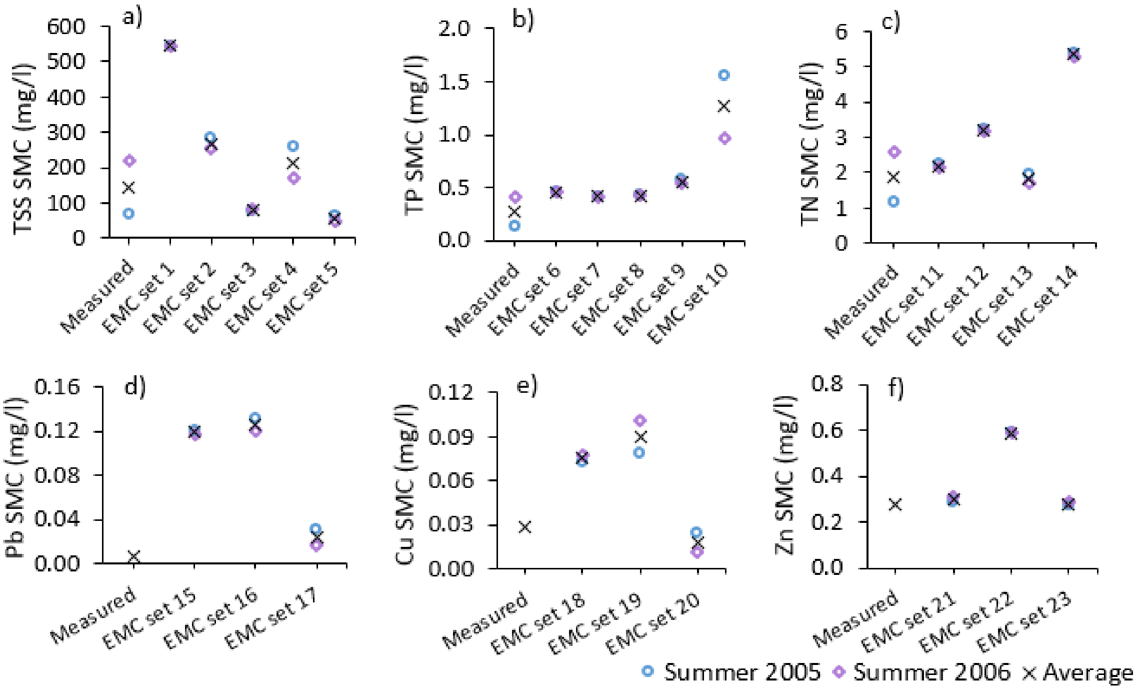

Figure 6. TSS (a), TP (b), TN (c), Pb (d), Cu (e) and Zn (f) SMCs for the rainy summer 2005 and the dry summer 2006, calculated from the runoff and loads simulated with different EMC sets (Table 3) from literature and compared with measured SMCs from Vallikallio and Lahti (Valtanen et al. 2014).

The SMCs varied between the simulations, but were in the same order of magnitude or larger than the measured SMCs (Figure 6). For the measured values from Vallikallio (Figure 6a-c), the SMC of the dry summer 2006 was at least double when compared with the rainy summer 2005. For the simulated results, the SMCs were the same order of magnitude for both summers, with a few exceptions. In general, the simulated SMCs were larger for the rainy summer 2005 than for the dry summer 2006.

The differences between the simulations and the measured SMCs (Figure 6) were similar to the difference between the simulated and measured pollutant loads (Figure 5). For TSS, TP and TN the SMCs of one simulation were clearly larger than the measured SMCs (e.g. EMC set 10 in Figure 6b), while the other simulations had SMCs with the same order of magnitude as the measured SMCs. For Pb and Cu the SMCs of one simulation were the same order of magnitude as the measured SMC (e.g. EMC set 17 in Figure 6d), while the other SMCs were clearly larger. For Zn, the SMCs of two simulations were similar to the measured SMC and the SMCs of one simulation were larger. The differences of the SMCs are explained by 1) different distributions of runoff from source areas during dry and rainy summers and 2) the magnitude difference between source area EMCs (Appendix 1).

Based on the quality simulations and calculations, the performance of each water quality simulation was evaluated and for further simulations, one EMC set yielding results closest to the measured values was chosen for each pollutant (Table 11).

Table 11. EMC sets (Table 3) chosen for each pollutant based on evaluations and comparison with measured values.

Pollutant	EMC set
Total Suspended Solids (TSS)	3
Total Phosphorus (TP)	6
Total Nitrogen (TN)	13
Lead (Pb)	17
Copper (Cu)	20
Zinc (Zn)	23

3.2 Source area contributions of pollutants

The source area contributions of runoff and pollutant loads of TSS, TP, TN, Pb, Cu and Zn were simulated for the summers 2005 and 2006. The simulated source area contributions of pollutants for each EMC set can be found in Appendix 2 and for the selected simulations (Table 11) in Figure 7. In general, the impermeable source areas contributed with the highest volumes of runoff as well as most of the stormwater pollutant loads. Especially parking areas, walkways and roads contributed major proportions of the total pollutant loads. For metals, especially Zn, roofs were also large contributors of pollutant loads. The rainy summer 2005 produced clearly larger pollutant loads than the summer 2006, see Figure 5 for total pollutant loads. The wet weather conditions were also reflected by the source area distributions in Figure 7, indicating an increased contribution of pollutants from vegetated areas.

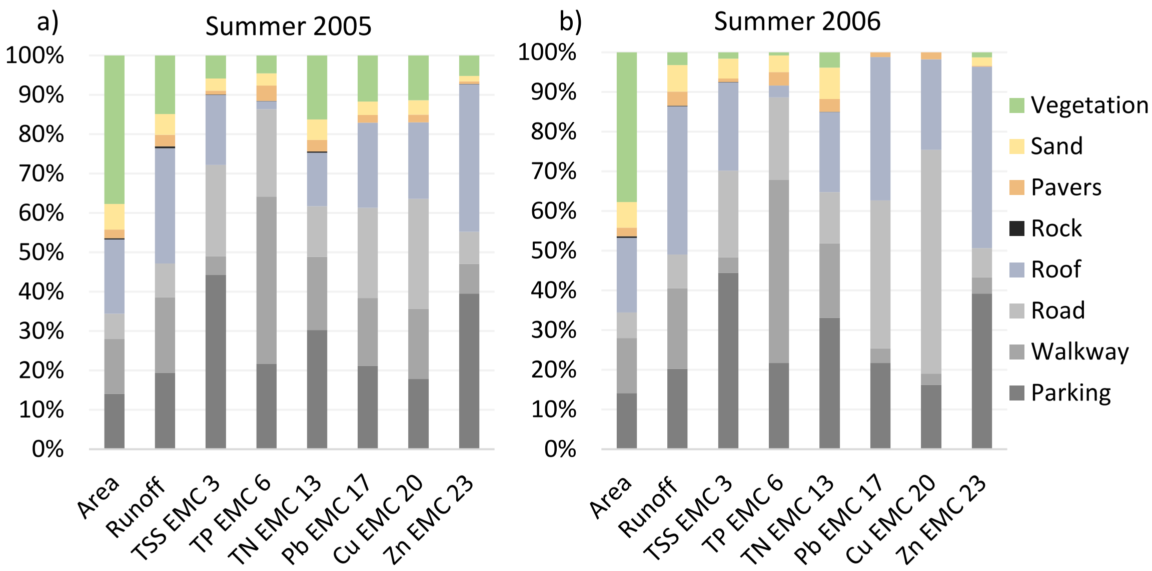

Figure 7. Source area distribution of the catchment area and source area contributions of runoff and each pollutant, simulated with selected EMC sets for summers 2005 (a) and 2006 (b).

In Vallikallio, over 50% of the land use is impermeable surfaces, such as asphalted traffic related areas and roofs. Around 40% is vegetated areas and the rest is stone or tile paved areas and sandy or gravelly areas. The runoff distribution from different land use areas differs from the land use distribution and there are differences between the runoff distributions of the summers 2005 and 2006 (Figure 7). Despite the rather large proportion of vegetated areas in Vallikallio, most of the runoff was produced from impermeable areas. Depending on the weather conditions of the two summers, the impermeable areas produced 75-85% of the total catchment runoff. The impact of the weather conditions was the most evident in the runoff generation from the vegetated areas: the runoff generated from the vegetated areas covered 5% and 15% of the total runoff during the dry summer 2006 and the rainy summer 2005, respectively.

For all pollutants, the pollutant contribution from impermeable source areas is over 75%, but for the rainy summer 2005 the average is around 85% and for the dry summer 2006 around 94% (Figure 7). Even with a similar distribution between contributions from impermeable and permeable source areas, the shares from different source areas varied between different pollutants. In general, parking areas and walkways were major pollutant contributors, but also roads and roofs. Sandy or gravelly areas contributed in general a few percent, during the dry summer more than the vegetated areas and during the rainy summer less than the vegetated areas. Open rock pollutant contribution was very small or negligible for all source areas, for both summers. Pollutant contributions from stone- or tile-paved source areas varied, but were in general small.

A major part (90-92%) of the TSS load originate from impermeable surfaces, mainly parking areas (44%), roads (22-23%) and roofs (18-22%) (Figure 7). The major contributors (88-92%) of TP loads were impermeable surfaces, especially walkways (42-46%), but also parking areas (22%) and roads (21-22%). The source area contribution of TN also originated mainly (76-85%) from impermeable source areas, such as parking areas (30-33%), walkways (19%) and roofs (14-20%). The source area contributors of the metals Pb, Cu and Zn is somewhat different to the source area distributions of TSS, TP and TN (Figure 7). Impermeable surfaces had even a larger contribution (83-99%), but especially roof areas were a major pollutant source for metals (19-46%). In addition, traffic-related areas, such as parking areas (16-40%) and roads (7-56%) were major contributors of metals.

3.3 Modelling stormwater management scenarios

3.3.1 Description of modelled management scenarios

Based on the simulated source area contributions of stormwater pollutants and the scope of the research project in filtration systems, the stormwater management scenarios focused on filtration structures on the most polluting impermeable source areas, including parking, walkways and roads. The filtration structures chosen were bioretention cells and permeable pavements. Six different management scenarios were formed. In each scenario, one of the LID controls was assumed to be located on either every parking area, walkway or road (Figure 8) in the catchment.

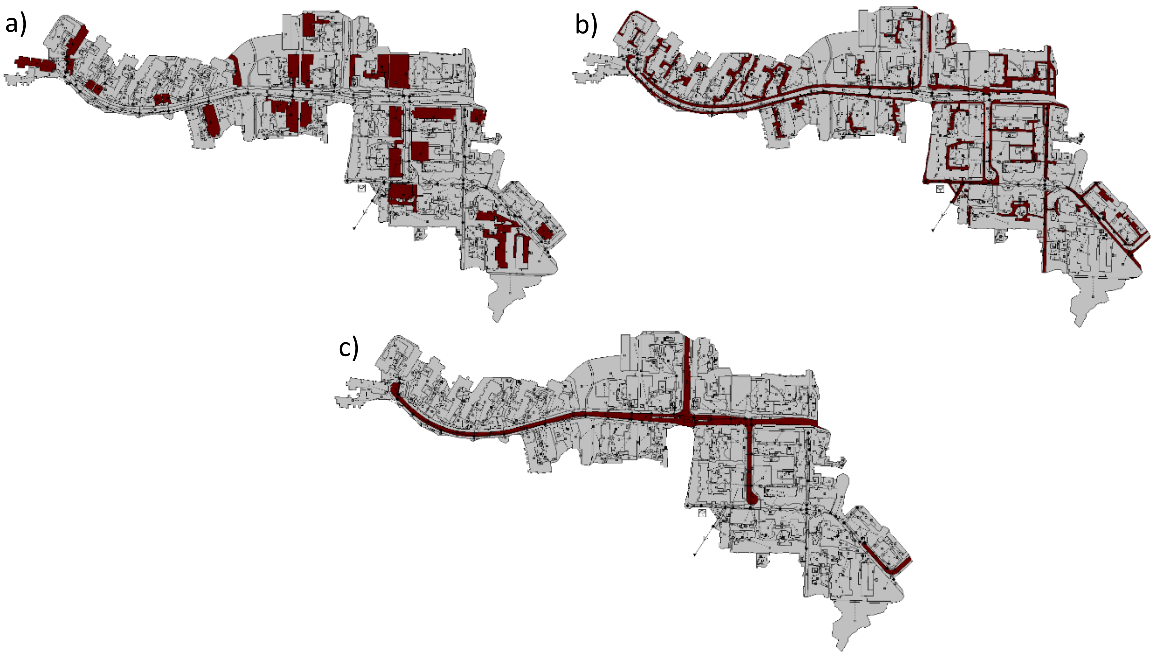

Figure 8. LID controls located at parking areas (a), walkways (b) and roads (c) in the Vallikallio catchment model. Specific source area is highlighted with red color.

Permeable pavements covered the whole subcatchment they were assigned to, while bioretention cells were parametrized to cover 5% of the subcatchment area. Thus, the total catchment area covered by permeable pavements is larger than the area covered by bioretention cells (Table 12). The structures of the LID controls are illustrated in Figure 4 and the chosen parameter values presented in Table 6 in Section 2.4.1.

Table 12. Modelled stormwater management scenarios and the area occupied by the LID control.

Scenario	LID control	Source areas	Area occupied (ha)	Area occupied (% of total catchment area)
1	Permeable pavement	Parking areas	1.6	14
2	Permeable pavement	Walkways	1.6	14
3	Permeable pavement	Roads	0.7	6
4	Bioretention cell	Parking areas	0.08	0.7
5	Bioretention cell	Walkways	0.08	0.7
6	Bioretention cell	Roads	0.04	0.3

3.3.2 Comparison of stormwater management scenarios

The simulated stormwater management scenarios were compared with each other and with the original model without any LIDs. The LID structures retain stormwater at the source and reduce runoff quantity while increasing infiltration and evaporation (Figure 9). All scenarios reduced the runoff, especially the permeable pavements on parking areas and walkways, although the runoff reduction by bioretention cells during the rainy summer 2005 was small. The increase of infiltration and evaporation was small.

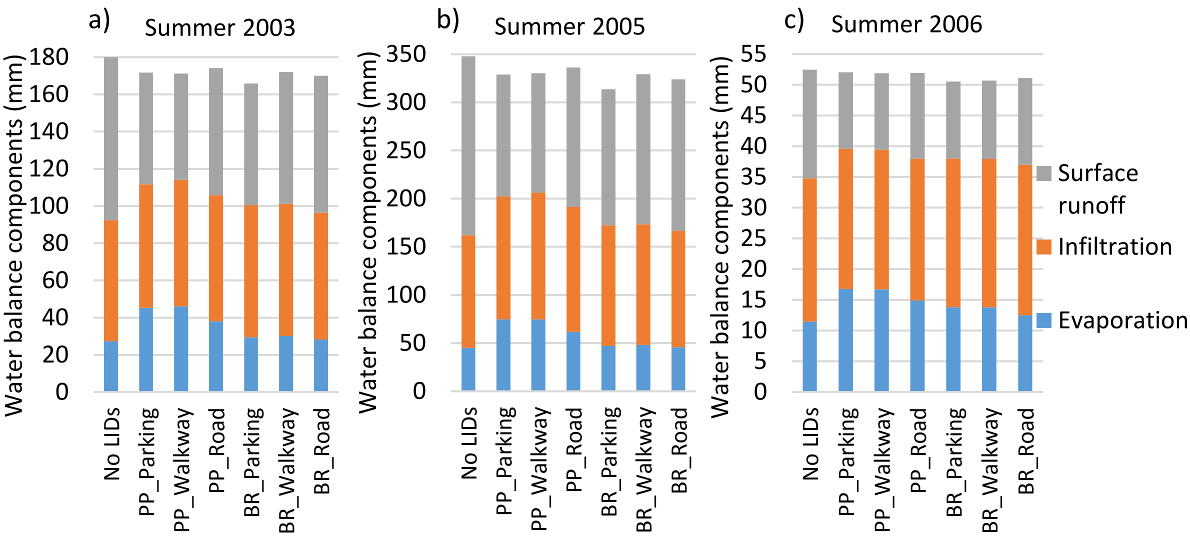

Figure 9. Surface runoff, infiltration loss and evaporation loss for the different LID scenarios and the model without any LIDs, for summers 2003 (a), 2005 (b) and 2006 (c).

During the dry summer 2006, the shares of runoff were the smallest (23-34%), compared with the larger shares of infiltration (41-47%) and evaporation (22-30%) (Figure 9). During the rainiest summer 2005, the share of runoff was the largest (35-53%) and the share of evaporation (13-21%) the smallest. The average summer 2003 had a similar distribution as the rainy summer, but with slightly larger shares of evaporation (15-25%) and infiltration (36-39%).

The total sums of the water balance components are smaller for the LID scenarios, than for the original model without LIDs (Figure 9). The differences were due to water storage within the LID structure and underdrain outflow from the LID structure. The underdrain outflow was larger for bioretention cells while the storage was larger for permeable pavements. During the rainier summers 2003 and 2005, especially the underdrain outflows were larger than during the dry summer 2006.

The total runoff and pollutant loads were calculated for each scenario and compared with the results from the model without LIDs (Table 13). In Table 13, the pollutant reduction is based only on the runoff reduction simulated in SWMM, because SWMM does not account for the pollutant processes within the LID units. The pollutant reduction rates were in general larger during the summers 2003 and 2006, whereas the increase in runoff generation during the rainy conditions in 2005 led to reduced pollutant reduction rates.

The scenarios reduced the different pollutants to varying extent, depending on the specific LID location and pollutant (Table 13). In general, the reduction rates of permeable pavements were higher than for bioretention cells. LIDs on parking areas had the largest pollutant reduction of TSS (22-47%), TN (14-35%) and Zn (19-41%). LIDs on walkways reduced TP (26-55%) efficiently, but poorly TSS (2-5%) and Zn (5-9%). Permeable pavements on roads reduced Pb (19-39%) and Cu (24-58%) quite efficiently, while poorly Zn (7-8%) and TN (8-13%). The walkways contributed with small shares of both TSS and Zn loads while roads contributed with relatively small shares of TN and Zn loads (Figure 7), thus management of runoff from these source areas cannot result in major total pollutant reductions for these pollutants.

Table 13. Runoff and total catchment pollutant loads for the different stormwater management scenarios, and runoff and load reductions calculated based on runoff reduction.

Scenario	Summer	Runoff		TSS		TP		TN		Pb		Cu		Zn	
		(m³)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)
Without LIDs	2006	2227		158		0.9		3		0.03		0.02		0.55	
	2003	10702		744		4.3		18		0.27		0.21		2.55	
	2005	22287		1559		9.2		39		0.59		0.49		5.31	
Parking Permeable pavement	2006	1775	20	84	47	0.7	23	2	35	0.03	22	0.02	15	0.32	41
	2003	8685	19	405	46	3.4	22	13	31	0.21	23	0.17	19	1.52	40
	2005	18445	17	856	45	7.4	20	28	29	0.48	20	0.41	16	3.18	40
Walkway Permeable pavement	2006	1789	20	152	4	0.4	55	3	23	0.03	23	0.02	30	0.52	6
	2003	8840	17	709	5	2.0	54	14	22	0.22	20	0.17	22	2.33	9
	2005	19402	13	1525	2	4.4	52	32	17	0.51	15	0.41	16	4.95	7
Road Permeable pavement	2006	2039	8	123	22	0.7	21	3	13	0.02	39	0.01	58	0.51	7
	2003	9880	8	577	22	3.4	21	16	11	0.21	23	0.15	29	2.35	8
	2005	21075	5	1220	22	7.7	16	35	8	0.48	19	0.37	24	4.96	7
Parking Bio-retention	2006	1831	18	88	44	0.7	21	2	32	0.03	22	0.02	15	0.33	40
	2003	9625	10	495	33	3.6	16	14	22	0.23	16	0.18	16	1.79	30
	2005	20942	6	1220	22	8.3	10	33	14	0.54	10	0.45	8	4.28	19
Walkway Bio-retention	2006	1876	16	153	3	0.4	50	3	20	0.03	21	0.02	26	0.52	6
	2003	9533	11	703	5	2.7	38	15	16	0.23	17	0.18	16	2.36	7
	2005	20764	7	1503	4	6.8	26	35	10	0.53	10	0.43	12	5.06	5
Road Bio-retention	2006	2121	5	131	17	0.7	15	3	9	0.02	30	0.01	45	0.52	6
	2003	10168	5	624	16	3.7	15	17	8	0.23	17	0.17	21	2.41	6
	2005	21667	3	1403	10	8.4	9	37	5	0.54	9	0.43	12	5.13	3

3.3.3 Pollutant reductions with pollutant removal rate for LIDs

The pollutant loads and reductions on a catchment scale for each scenario (Table 14) were recalculated using pollutant removal rates (Table 8) to consider also the pollutant reduction benefits of the LID structure, and not only runoff volume-based reduction. The pollutant reduction rates increased especially for the wet summer 2005 and are more even between the different summers when compared with the reduction rates calculated only based on runoff (Table 13).

The inclusion of pollutant reduction in the LID controls had a large impact on the pollutant loads for scenarios involving bioretention cells. For bioretention cells, the pollutant reduction increased during all summers. Especially the TSS (from 22 to 44%) and Zn (from 19 to 38%) reduction increased during summer 2005 from the bioretention LIDs located on parking areas. For the bioretention LIDs located on walkways, there was a big increase in reduction of TP (from 26 to 46%). The inclusion of pollutant retention within the LID units had only small effect on the overall pollutant reduction of scenarios with permeable pavements (Table 14). However, the pollutant reduction during the rainy conditions of summer 2005 increased, especially for TN (from 17 to 23%), Cu (from 16 to 22%) and Pb (from 15 to 21%) on walkways and TP (from 16 to 22%) on roads.

Table 14. Runoff and total catchment pollutant loads for the different stormwater management scenarios, and runoff and load reductions calculated based on pollutant removal rates (Table 8).

Scenario	Summer	Runoff		TSS		TP		TN		Pb		Cu		Zn	
		(m³)	*(%)*	(kg)	*(%)*	(kg)	*(%)*	(kg)	*(%)*	(kg)	*(%)*	(kg)	*(%)*	(kg)	*(%)*
Without LIDs	2006	2227		158		0.9		3		0.03		0.02		0.55	
	2003	10702		744		4.3		18		0.27		0.21		2.55	
	2005	22287		1559		9.2		39		0.59		0.49		5.31	
Parking Permeable pavement	2006	1775	*20*	84	*47*	0.7	*23*	2	*35*	0.03	*22*	0.02	*15*	0.32	*41*
	2003	8685	*19*	404	*46*	3.3	*22*	13	*31*	0.21	*23*	0.17	*19*	1.51	*41*
	2005	18445	*17*	835	*46*	7.1	*23*	26	*32*	0.46	*23*	0.39	*19*	3.12	*41*
Walkway Permeable pavement	2006	1789	*20*	152	*4*	0.4	*55*	3	*23*	0.03	*23*	0.02	*30*	0.52	*6*
	2003	8840	*17*	704	*5*	2.0	*55*	14	*24*	0.22	*21*	0.16	*23*	2.32	*9*
	2005	19402	*13*	1475	*5*	4.2	*55*	30	*23*	0.47	*21*	0.38	*22*	4.83	*9*
Road Permeable pavement	2006	2039	*8*	123	*22*	0.7	*21*	3	*13*	0.02	*39*	0.01	*58*	0.51	*7*
	2003	9880	*8*	574	*23*	3.4	*22*	16	*12*	0.21	*24*	0.15	*30*	2.34	*8*
	2005	21075	*5*	1199	*23*	7.2	*22*	34	*12*	0.46	*23*	0.35	*27*	4.88	*8*
Parking Bio-retention	2006	1831	*18*	84	*47*	0.7	*23*	2	*34*	0.03	*22*	0.02	*15*	0.32	*41*
	2003	9625	*10*	412	*45*	3.4	*22*	13	*29*	0.21	*22*	0.17	*19*	1.55	*39*
	2005	20942	*6*	880	*44*	7.2	*22*	28	*28*	0.47	*21*	0.40	*17*	3.28	*38*
Walkway Bio-retention	2006	1876	*16*	152	*4*	0.4	*55*	3	*22*	0.03	*21*	0.02	*26*	0.52	*6*
	2003	9533	*11*	692	*7*	2.2	*49*	14	*21*	0.22	*20*	0.17	*20*	2.32	*9*
	2005	20764	*7*	1462	*6*	4.9	*46*	31	*19*	0.48	*19*	0.39	*19*	4.87	*8*
Road Bio-retention	2006	2121	*5*	124	*22*	0.7	*21*	3	*12*	0.02	*38*	0.01	*56*	0.51	*7*
	2003	10168	*5*	577	*22*	3.4	*22*	16	*12*	0.21	*23*	0.15	*29*	2.35	*8*
	2005	21667	*3*	1208	*23*	7.2	*22*	34	*11*	0.46	*22*	0.36	*26*	4.90	*8*

3.4 Rainfall, runoff and pollutant distributions in Vallikallio

The rainfall and runoff distributions for the Vallikallio catchment (Figure 10) shows that most storms are small or intermediate, and that these storms are major contributors of runoff. Around 55% of the storm events had a rain depth less than 4 mm and generated around 5% of the total runoff volume. Rain depths larger than 4 mm started to increase the runoff volume. Around 95% of the storm events had a rain depth less than 20 mm and generated around 65% of the total runoff volume. Only a few percent of the storm events were large events that produced large runoff volumes. The 10 mm rain depth used in the current Finnish design practice accounted for 80% of all storm events and these storms generated only 30% of the total runoff volume.

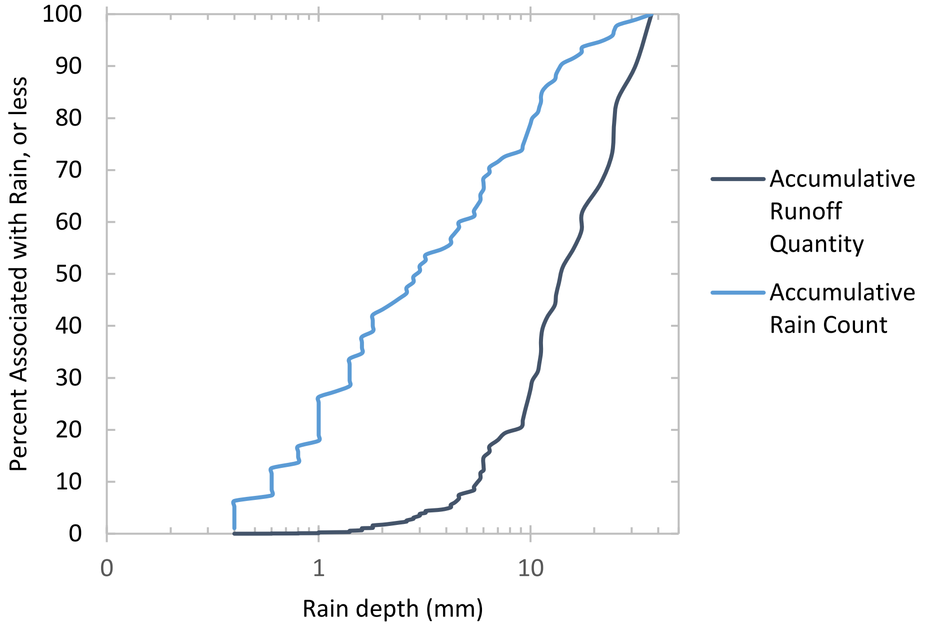

Figure 10. Rainfall and runoff distributions for Vallikallio for the summers 2003, 2005 and 2006.

The pollutant load distribution of TSS, TP, TN, Cu, Zn and Pb for the Vallikallio catchment (Figure 11) follows the shape on the runoff distribution (Figure 10). There were only minor differences between the distributions of the different pollutants. Pollutant loads were generated to a similar extent as runoff volume. Intermediate rains generated the largest runoff volumes, and thus pollutant loads. The rain depth of 10 mm generated 19-24% of the pollutant loads while the rain depth of 20 mm generated 58-63% of the pollutant loads.

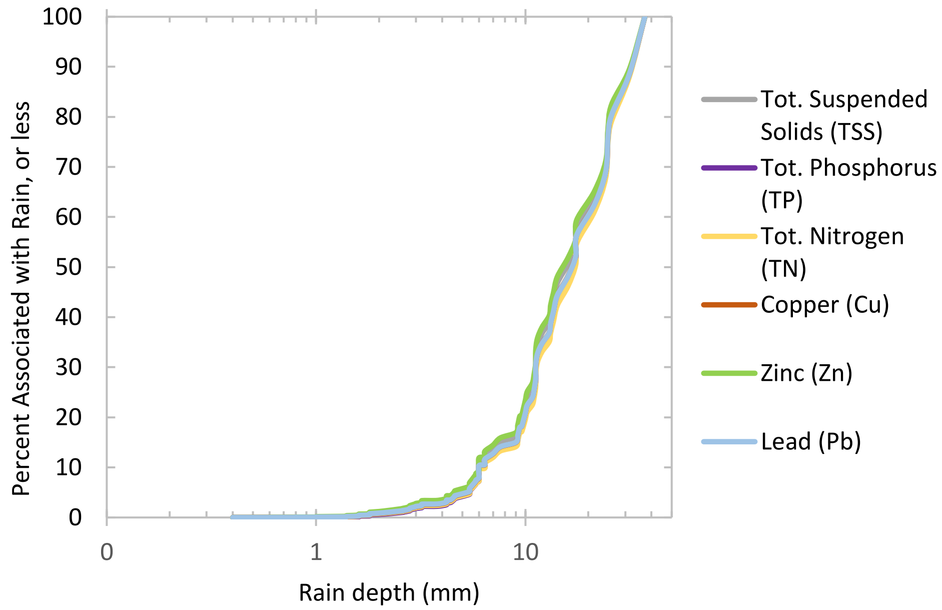

Figure 11. Pollutants load distributions for Vallikallio for the summers 2003, 2005 and 2006.

The runoff distribution for different catchment types (Figure 12), with varying TIAs, produced runoff distributions differing from the runoff distribution simulated for Vallikallio. The simulated runoff distribution for Vallikallio showed a smaller runoff volume for rain depths less than 10 mm, when compared with the other catchment types with runoff estimated from runoff coefficients. For the different catchment types, a 4 mm rain depth generated 9-12% of the runoff volume, a 10 mm rain depth generated 26-37% of the runoff volume and a 20 mm rain depth generated 52-69% of the runoff volume.

The different catchment types in Figure 12 produced slightly varying runoff distributions. The catchment type with a TIA of 0.9, representing a dense city-center or commercial area, showed a runoff distribution that produced the largest runoff from the same sized rain depths, when compared with the other catchments. The catchment type with a TIA of 0.2, representing a low-density residential area, showed a runoff distribution that produced the least runoff from the same sized rain depths.

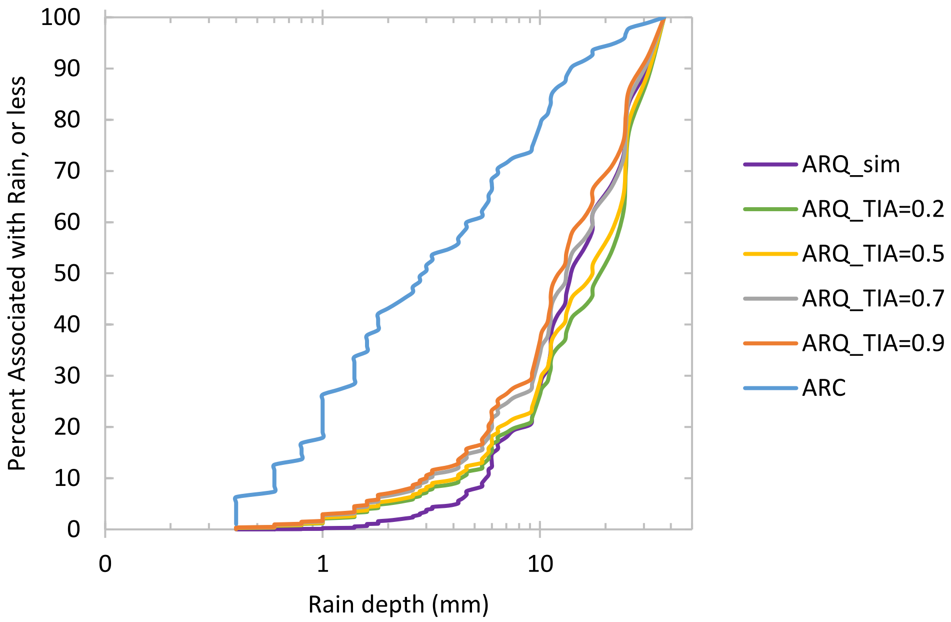

Figure 12. Runoff distributions for different catchment types, with varying TIAs, as well as the simulated runoff distribution for Vallikallio.

3.4.1 Rain categories for Vallikallio

Based on the rainfall and runoff distributions for Vallikallio, three different rain categories were determined by rain depth (Table 15). The rain depth breakpoints for the categories were defined to be 5 mm and 26 mm. The first category, small rains, were generated by a large part of the rain events, but the generated runoff volumes were small. The second category, intermediate rains, were generated by a smaller part of rain events, but these rains generated the largest runoff volumes. The third category, large rains, were only a few percent of the rain events, but still produced large runoff volumes.

Table 15. Rain categories determined for Vallikallio, based on rainfall and runoff distributions.

Category	Small rains	Intermediate rains	Large rains
Rain depth (mm)	<5	5-26	>26
Percent of rain events (%)	60	38	2
Percent of runoff produced (%)	8	76	16
Percent of pollutant loads produced (%)	5-6	75-77	17-20

4 Discussion

4.1 Evaluating source area contributions

According to Heaney *et al.* (1999), several factors from weather conditions to area characteristics affect the runoff and pollutant contribution from source areas. The characteristics of the source area that affect the generation of pollutant loads are according to Bannerman *et al.* (1993), the size, amount of connected imperviousness, type of material, traffic volume and soil type. Fraga *et al.* (2016) suggested that the main source area characteristics are the relative contributing area of the source area, as well as the physical surface and material. In the Vallikallio catchment, the largest shares of the source areas were vegetated areas (38%), followed by roofs (19%), parking areas (14%) and walkways (14%). Vehicular roads covered only 6% of the residential catchment, which also affects the load contribution. Source areas with a small area, such as open rock and paved areas had a minor impact on the runoff and pollutant loads. Hence, in future simulations these small source areas could be neglected in similar catchments.

Constructed impermeable areas are often emphasized as the key source areas for urban diffuse pollution for most pollutants (Bannerman *et al.* 1993; Waschbusch *et al.* 1999). Based on the simulation results in this study, the pollutant loads were mainly contributed from the impermeable areas in the catchment, such as parking areas, walkways, roads and roofs (Figure 7). From parking areas, especially large shares of TSS and Zn loads were generated, as well as the other simulated pollutants. Walkways contributed with especially large shares of nutrients. Roads contributed with large shares of the metals Pb and Cu, but also TSS and TP. According to Bannerman *et al.* (1993), parking areas are critical source areas especially in commercial and industrial land uses, and roads are critical source areas for most pollutants and contribute with the largest pollutant loads. In line with this, Waschbusch *et al*. (1999) and Pitt *et al.* (2004) reported that roads are the largest contributors of solids, especially during small low-intensity rains. In this study, the parking areas in Vallikallio were larger pollutant contributors than roads, except for Pb and Cu. The difference is partly due to the concentrations used for the source areas, and due to the size of parking areas being twofold when compared with the area of roads. The roads proved to be significant contributors of Pb and Cu, which is related to the high concentrations used in the simulations. On the other hand, according to Göbel *et al.* (2007), the source area concentrations of parking areas are usually overrated because of few investigations and lack of data from parking areas. When compared with roads, the traffic densities on parking areas are usually much lower, even though drip losses from cars may be higher on parking areas (Göbel *et al.* 2007).

According to Fraga *et al*. (2016), roads, parking areas and roofs are major contributors of TSS, Pb, Cu and Zn. In this study, the roofs in Vallikallio contributed with the largest proportional loads of metals, especially Zn. Pitt & McLean (1986), Bannerman *et al.* (1993) and Petrucci *et al*. (2014) reported in line with this that roofs are significant source areas for Zn contribution. The roof area in Vallikallio is the second largest after vegetated areas, which explains the large pollutant contributions. The reasons behind the high reported concentrations of Zn, Cu and Pb in roof runoff are the roof materials used (Bannerman *et al.* 1993; Borris *et al.* 2017). Thus, the heavy metal contribution of roofs varies depending on the roof materials used in the local catchment, and cannot be determined only based on literature values.

The stormwater pollutant generation in Vallikallio was affected by the local weather conditions. During the rainy summer, pervious vegetated areas were activated and produced more runoff and larger pollutant loads (Figure 5). Pitt *et al.* (2004) observed that pervious surfaces, such as vegetated areas, become important contributors especially of solids during larger storms. In Vallikallio, the vegetated areas contributed mostly with TN, TSS and TP, and an increase was noted during the rainy summer (Figure 7). In relation to the pollutant contributions from impervious source areas, the contribution of pollutants from vegetated areas was still small.

Larger rainfall generated larger loads, which were proportional to the increased runoff. Because of the use of constant EMCs for pollutants, the weather conditions did not affect the pollutant concentrations. The simulated SMCs were in general smaller for the dry summer and larger for the rainy summer (Figure 6). Usually, as for the measured SMCs, a larger runoff dilutes the pollutant concentrations and thus yields smaller SMCs than compared with dry circumstances. The simulations overestimate the pollutant loads during rainy conditions, because the constant EMCs do not reflect the dilution of pollutant concentrations observed by Sillanpää and Koivusalo (2015) during large rainfall events.

4.2 Performance of different LID management scenarios on pollutant loads

Based on the modelling of source area contributions, the focus of the LID management scenarios was on parking areas, walkways and roads (Figure 8). The different scenarios, with permeable pavements or bioretention cells, reduced the runoff and stormwater pollutants on a catchment scale to a different extent (Table 13). The SWMM quality simulations are only based on runoff reduction, and thus the inclusion of pollutant removal rates for the LID structures increased the simulated pollutant reductions (Table 14). Without inclusion of pollutant removal rates, the reduction results were better for permeable pavements, mainly due to the aerial extent of the LID controls and a larger treatment unit capacity in comparison to biofiltration systems.

Not one single scenario could be chosen to be the most effective for reducing every pollutant. In general, LIDs on parking areas generated good pollutant load reductions for several pollutants, mainly due to their large areal extent. Guan *et al.* (2015) studied the effects of common LIDs on urban runoff generation and concluded that the most effective management would be a combination of several different LIDs. A combination of LIDs controlling both runoff volumes and retention times led to more effective runoff reduction, but the reduction effect declined during larger storms (Guan *et al.* 2015). In the study of Bannerman *et al.* (1993) the most cost-effective stormwater management solution, in terms of controlling pollutant loads, was LID practices located on both streets and parking areas. The results of the current study support this conclusion; however, for particular pollutants, such as Zn, roofs may be the greatest source.

The simulated LID scenarios reduced the generated surface runoff while slightly increasing the infiltration and evaporation (Figure 9). For LID structures, the soil characteristics determine the significance of the infiltration (Field & Sullivan 2003). In the LID modelling of this study, a soil type with low hydraulic conductivity was used, which may explain the rather low increase in infiltration rates for the LID structures.

4.3 Management of storm events

The rain categories determined based on the Vallikallio rainfall data indicated that small and intermediate rains accounted for 98% of the rain events and produced 84% of all runoff (Table 15). The pollutant load distribution (Figure 11) followed the shape of the runoff distribution (Figure 10), generating pollutant loads in relation to runoff volume. Borris *et al.* (2014) modelled the effects of rainfall event characteristics on TSS load in urban runoff with SWMM, and concluded that the relatively frequent storm events contribute with a high percentage of the annual pollutant load.

The focus of stormwater quality management can vary depending on the objectives. If the objective is to reduce the storm events exceeding water quality standards, which usually are measured in concentrations, the focus should be on small rains. If the objective is to reduce long-term pollutant loads, the focus should be on intermediate rains. The large rains are important for drainage design and flood control, but the large events are rare and do not significantly contribute to annual pollutant loads (Heaney *et al.* 1999).

The 10 mm rain depth used in the Finnish design practice of stormwater management controls accounted for 80% of all storm events in Vallikallio, but the cumulative runoff volume and pollutant loads corresponded only to 30% and 19-24%, respectively. The largest part of the cumulative runoff volume and pollutant loads are generated from intermediate rains and the category was determined to contain a large range of rain depths from 5 to 26 mm. A 10 mm storm covers a large part of the storm events, but if the focus is on effective pollutant load reduction, the storage volume for design should be found within the range of 10-26 mm rain depth. Sillanpää & Koivusalo (2014) and Guan *et al.* (2016) have earlier determined that urban runoff is mainly formed from impermeable surfaces when the rain depth is less than 17-20 mm. If the management is focused on stormwater originating from constructed impermeable surfaces, as roofs and traffic-related areas, the storage volume should be increased to rain depths of 10-20 mm. Overall; the selection of a storage volume for management design should be based on simulations of long-term pollutant load generation instead of single design storms.

Based on the simulations, the stormwater pollutant loads are diffuse and there are more than one source area contributing with pollutants (Figure 7). In addition, the relevance of different source areas varies between pollutants. For stormwater management, it is still important to understand the mechanisms of the source areas within a catchment. If roofs are considered significant source areas within a catchment, as it is for some metal loads (Pitt & McLean 1986; Bannerman *et al.* 1993; Petrucci *et al.* 2014), LID structures located on roads are not efficient if the roof area is large and the untreated roof runoff is directed to the stormwater sewer system. On the other hand, if parking areas are considered significant source areas (Bannerman *et al.* 1993), the allocation of LID structures could there result in positive results regarding pollutant reduction.

4.4 Quantity and quality modelling

The water quantity and quality models are complex with connected subcatchments, sewer systems and LID controls, and the processes in the model should according to Niazi *et al.* (2017) be represented in a simplified way to gain high computational speed in model execution. To control the computational burden and obtain feasible calibration and validation, simplified model representations have proven to be legitimate in hydrologic applications (Niazi *et al.* 2017). Depending on the goal of the modelling, simplifications can also be considered as a limitation if a detailed model is required (Niazi *et al.* 2017).

In the current study, it was noticed that large uncertainties are related to stormwater quality modelling, especially related to lack of local measurements. On the other hand, stormwater quality modelling is essential for designing efficient decentralized LID structures.

In stormwater modelling the catchment is usually grouped based on land use categories, which commonly are residential, commercial and industrial areas. By roughly grouping based on the land use, the catchment characteristics are variable, while the model is still kept simple. It can be necessary to further separate the source areas according to detailed land use, since the runoff distributions and pollutant concentrations vary between different surfaces (Göbel *et al.* 2007). The source areas and their properties are easily parametrized to a subcatchment in SWMM, but the runoff and pollutant contributions of each source area are not directly obtainable from SWMM, rather calculated based on runoff and classification of subcatchments in the model. In this study, the street areas were further divided into walkways and vehicular roads, which decreased the area covered by roads and thus affected the source area contributions.

Using EMCs, as in this study, is a simpler approach than parameterizing the buildup-washoff functions, and according to Rossman and Huber (2016b) the most common approach used for the estimation of pollutant loads. Modelling stormwater quality with the buildup-washoff approach requires extensive effort to produce water quality predictions, due to parameter estimation and model calibration (Rossman & Huber 2016b). Niazi *et al.* (2017) reported that SWMM studies with an event-based calibration are more popular than continuous calibration. According to Tan *et al.* (2008), continuous calibration should be implemented when the main concern of the study is runoff volume estimation, while event-based calibration performs better, when the concern is the shape of the hydrograph and peak flows. Considering the effects on receiving water quality, the most important information is the pollutant load (Rossman & Huber 2016b). In this study, the creation of a simple quality model based on constant EMCs proved to be challenging, the simulated pollutant loads are highly variable and involve large uncertainties. It can be assumed that even if the total pollutant load is uncertain, the results still give a picture about the relevance of different source areas in relation to the others.

The quality simulations yielded pollutant loads of varying magnitude (Figure 5) and the evaluation of the simulations was based on comparison to measured loads at the catchment outlet. Some simulations yielded pollutant loads clearly larger than the measured values. In a study of Bannerman *et al.* (1993), the simulated summed source area loads were larger than the measured source area loads, which indicated that not all pollutants were transported to the outlet. It is difficult to evaluate the validity of the simulated pollutant loads based only on outlet measurements. Comparison against measured outlet loads does not necessarily generate the most realistic results, even though it is the best available data for validating the quality simulations. In regular design situations, local measurements are rarely available, or at least not from detailed source areas. The results indicate, that estimating source area contribution based on literature results in large uncertainties and highlights the importance of local measurements, but are still feasible if no other data is available.

On the other hand, the differences between simulated and measured outlet loads can be due to literature EMCs that does not correspond to the conditions in the local catchment or due to the processes occurring from the source area to the sewer system. The processes occurring on the pathway from the source area to the sewer system and inside of the sewer pipes are complex or not studied in detail. According to Bannerman *et al*. (1993), there may be potential problems with understanding the transport of stormwater pollutants. Borris *et al.* (2017) studied the implications of sewer pipe materials on the water quality and heavy metal transport and reported a reduction in turbidity and changes in concentrations depending on the metal and material. Bannerman *et al.* (1993) suggested that to reduce the error between measured and simulated outfall loads, some kind of pollutant transport function would be needed in the modelling process. Currently, it is possible to model pollutant treatment and decay in SWMM by assigning removal rates to the nodes in the model (Niazi *et al.* 2017), but this feature was not utilized in the simulations of this study.

The quality modelling of LID structures with SWMM is currently relatively simple, since the internal processes of the LID structures, or processes such as the sedimentation of solids are not considered. Niazi *et al.* (2017) presented a performance review and gap analysis for SWMM, and assessed the performance of water quality simulations regarding LID design. One gap in SWMM recognized by Niazi *et al.* (2017) was related to the absence of transport processes for stormwater pollutants in buildup and washoff, overland flow, sewer systems or inside LID structures. In SWMM, the pollutant removal rates could be a part of the LID structure parametrization, instead of only a feature in the model nodes.

As the application of LID structures becomes common, it is important to evaluate their performance. According to Niazi *et al.* (2017), there is a need to study and evaluate the modelling performance and ability to simulate the management alternatives with SWMM. Ingvertsen *et al*. (2011) presented a minimum set of water quality parameters that should be assessed to compare the treatment efficiencies of LID structures. In addition to fine suspended solids, the concentrations of Zn, Cu, phosphorus and nitrogen, the minimum set also included the concentrations of a few polycyclic aromatic hydrocarbons (PAH) compounds (Ingvertsen *et al.* 2011), which were not simulated in this study.

There are large uncertainties in the simulation of urban runoff quality. According to Fraga *et al.* (2016), stormwater models may perform well when stormwater is routed and runoff predicted, but the stormwater quality predictions are non-specific and limited. The results from surface runoff quality modelling can be assumed to be hypothetical if there are no local measurements available for validation and calibration (Rossman & Huber 2016b). In this study, local measurements were available from the catchment outlet, but not from source areas within the catchment. For accurate information about source area contributions, the source areas within the catchment should be monitored. Since local measurements are not always available or possible to obtain, this study provides important information related to uncertainties of literature values. On the other hand, the EMC sets used in this study can be utilized in the modelling of similar catchments, as long as the uncertainties are recognized.

5 Conclusions

The main objectives of this study were to model the source area contributions of stormwater pollutants and LID filtration structures, and to assess the impacts on runoff and pollutants on a residential catchment scale. The objectives were motivated by a need to develop water quality modelling and to enhance stormwater quality management. Information about the source area contributions is needed to prioritize management options and prevent pollution.

The first research objective (1a) was to evaluate the applicability of using EMCs from literature for stormwater quality modelling. EMCs for each source area and pollutants were chosen from literature and combined to different sets. Based on the simulations and comparison to measured loads, one simulation for each pollutant was chosen. In general, the simulations produced varying loads and load contributions from different source areas. EMCs from literature are usually based on local monitoring, which might differ from the conditions of the study site and local circumstances. This should be kept in mind when analyzing stormwater EMCs and results, because there might be a big difference in the frequency and amount of precipitation affecting the concentration. Using EMCs is a simple and commonly used approach, but measurements from the catchment are needed to validate the results. Often local measurements are not available, and thus the EMCs documented in this study could be applied to other local catchments with similar conditions.

The second part of the first research objective (1b) was to evaluate the source areas and their generation of pollutant loads. Impermeable areas, as parking areas, walkways, roads and roofs, contributed most of the stormwater loads. Roofs contributed especially with heavy metal loads. Rainy weather conditions affected the load generation by increasing the pollutant generation from vegetated areas. Based on the results, one source area type cannot be considered more important regarding pollutant contribution than the other source area types. The pollutant contributions depend on the characteristics, such as area proportions and on how accurate information of stormwater quality is available.

The second research objective was to model LID filtration structures in a catchment, and to evaluate their impact on the pollutant loads. Bioretention cells and permeable pavements were simulated on parking areas, roads and walkways. The simulated LID scenarios reduced the amount of surface runoff, by slightly increasing the infiltration and evaporation. Based on the SWMM simulations, considering only runoff reduction, the pollutant reductions were moderate especially for the simulations with bioretention cells. Applying pollutant removal rates for the LID structures increased the pollutant reduction also on a catchment scale. The scenarios reduced pollutants to a different extent, depending on the location and pollutant. For targeting all of the simulated pollutants, a combination of several different decentralized LID controls could be the most effective management option.

The results of the study indicate that stormwater quality modelling with SWMM is rather challenging, as well as drawing conclusions from the uncertain results. In the absence of local monitoring data, modelling is important for developing management, and regulations for stormwater quality, as well as requirements for pollutant reductions, and should thus be further developed and utilized. Current challenges with modelling stormwater quality with SWMM are related to the difficulties of directly extracting source area contributions from the simulated results and the non-existent possibilities to incorporate pollutant reduction processes directly to the LID unit parametrization. As well as challenges related to modelling the removal processes related to the transport of stormwater pollutants along the runoff pathways from source areas to sewer manholes and within the sewer system.

The third research objective was to analyze the rainfall, runoff and pollutant distributions of Vallikallio and to determine rain categories as a part of stormwater management. Small and especially intermediate rains contribute with significant runoff volumes and pollutant loads, and should be key rains in stormwater quality management. Design of stormwater management controls should be based on simulations of long-term rainfall data and pollutant load generation rather than single design storms.

The catchment characteristics and the relation to pollutant concentrations and loads are important for the stormwater management. By identifying the source areas contributing most pollutants, the amount of area needed for LIDs could be reduced and cost-effective stormwater quality management achieved. For the design of decentralized LID controls, the source area contributions and their significance should always be evaluated in the scale of the design area and catchment.

References

Aaltonen, J. 2008. Sadanta-valuntaprosessi taajama-alueella: MOUSE ja MIKE SHE–ohjelmien testaaminen (Rainfall-runoff process in urban catchment: The testing of MOUSE and MIKE SHE Software). Master's thesis. Helsinki University of Technology, Faculty of Engineering and Architecture. Espoo, Finland. 113 p.

Bannerman, R.T., Owens, D.W., Dodds, R.B. & Hornewer, N.J. 1993. Sources of pollutants in Wisconsin stormwater. Water Science and Technology. Vol. 28 (3-5). P. 241-259.

Barbosa, A.E., Fernandes, J.N. & David, L.M. 2012. Key issues for sustainable urban stormwater management. Water Research. Vol. 46. P. 6787-6798. DOI:10.1016/j.watres.2012.05.029.

Borris, M., Österlund, H., Marsalek, J. & Viklander, M. 2017. An exploratory study of the effects of stormwater pipeline materials on transported stormwater quality. Water Science and Technology. DOI: 10.2166/wst.2017.195.

Borris, M., Viklander, M., Gustafsson, A-M. & Marsalek, J. 2014. Modelling the effects of changes in rainfall event characteristics on TSS loads in urban runoff. Hydrological Processes. Vol. 28. P. 1787-1796. DOI:10.1002/hyp.9729.

Burns, M.J., Fletcher, T.D., Walsh, C.J., Ladson, A.R. & Hatt, B.E. 2012. Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. Landscape and Urban Planning. Vol. 105. P. 230-240. DOI:10.1016/j.landurbplan.2011.12.012.

Burton, G.A. & Pitt, R.E. 2002. Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists, and Engineers. CRC Press. ISBN: 0-87371-924-7. 929 p.

Cities of Espoo, Helsinki and Vantaa. 2017. Helsinki Metropolitan Area Guide Map [Online]. Available at: https://kartta.helsinginseutu.fi/index_en.html?zoom=0&lat=6674839.59991&lon=25496566&layers=B0TT. [Accessed 10.8.2017].

Duncan, H.P. 1999. Urban Stormwater Quality: A statistical Overview. Report 99/3. Cooperative Research Centre for Catchment Hydrology. ISBN: 1876006455. 134 p.

Elliott, A.H. & Trowsdale, S.A. 2007. A review of models for low impact urban stormwater drainage. Environmental Modelling & Software. Vol. 22. P. 394-405. DOI:10.1016/j.envsoft.2005.12.005.

Field, R. & Sullivan, D. 2003. Wet-weather flow in the urban watershed: Technology and management. CRC Press LLC, Boca Raton, Florida, USA. ISBN: 1-56676-916-7. 384 p.

Fraga, I., Charters, F.J., O'Sullivan, A.D. & Cochrane, T.A. 2016. A novel modelling framework to prioritize estimation of non-point source pollution parameters for quantifying pollutant origin and discharge in urban catchments. Journal of Environmental Management. Vol. 167. P. 75-84. DOI: 10.1016/j.jenvman.2015.11.003.

Gilbert, J.K. & Clausen, J.C. 2006. Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut. Water Research. Vol. 40. P. 826-832. DOI:10.1016/j.watres.2005.12.006.

Guan, M., Sillanpää, N. & Koivusalo, H. 2016. Storm runoff response to rainfall pattern, magnitude and urbanization in a developing urban catchment. Hydrological Processes. Vol. 30. P. 543-557. DOI: 10.1002/hyp.10624.

Guan, M., Sillanpää, N. & Koivusalo, H. 2015. Assessment of LID practices for restoring pre-development runoff regime in an urbanized catchment in southern Finland. Water Science & Technology. Vol. 71(10). P. 1485-1491. DOI: 10.2166/wst2015.129.

Göbel, P., Dierkes, C. & Coldewey, W.G. 2007. Storm water runoff concentration matrix for urban areas. Journal of Contaminant Hydrology. Vol. 91. P. 26–42. DOI:10.1016/j.jconhyd.2006.08.008.

Harremoës, P. 1988. Stochastic models for estimation of extreme pollution from urban runoff. Water Research. Vol. 22(8). P. 1017-1026.

Heaney, J.P., Pitt, R. & Field, R. 1999. Innovative Urban Wet-Weather Flow Management Systems. Cincinnati, Ohio. U.S. Environmental Protection Agency. EPA/600/R-99/029. 568 p.

Huber, W.C., Cannon, L. & Stouder, M. 2006. BMP Modeling Concepts and Simulation. U.S. Environmental Protection Agency. EPA/600/R-06/033. 166 p.

Ingvertsen, S.T., Bergen Jensen, M. & Magid, J. 2011. A Minimum Data Set of Water Quality Parameters to Assess and Compare Treatment Efficiency of Stormwater Facilities. Journal of Environmental Quality. Vol. 40. P. 1488-1502. DOI:10.2134/jeq2010.0420.

Karttunen, E. 2004. Vesihuolto 2 (*Water supply 2*). RIL 124-2. Suomen rakennusinsinöörien liitto ry. Helsinki, Finland. ISBN: 951-758-438-5. 684 p.

Kling, T., Holt, E., Kivikoski, H., Korkealaakso, J., Kuosa, H., Loimula, K., Niemeläinen, E. & Törnqvist, J. 2015. Vettä läpäisevät päällysteet: Käsikirja suunnitteluun, rakentamiseen ja ylläpitoon. (*Permeable pavements: Guidance for planning, construction and maintenance*). VTT Technology 201. VTT Technical Research Centre of Finland. ISBN: 978-951-38-8198-6.

Lee, J.G. & Heaney, J.P. 2003. Estimation of urban imperviousness and its impacts on storm water systems. Journal of Water Resources Planning and Management. Vol. 129(5). P. 419-426. DOI: 10.1061/(ASCE)0733-9496(2003)129:5(419).

Leopold, L.B. 1968. Hydrology of urban land planning – A guidebook on the hydrologic effects of urban land use. Geological Survey Circular, 554. U.S. Department of the Interior, Washington, USA.

Niazi, M., Nietch, C., Maghrebi, M., Jackson, N., Bennett, B., Tryby, M. & Massoudieh, A. 2017. Storm Water Management Model: Performance Review and Gap Analysis. Journal of Sustainable Water in the Built Environment. Vol. 3(2). ISSN: 2379-6111.

Petrucci, G., Rodriguez, F., Deroubaix, J-E. & Tassin, B. 2014. Linking the management of urban watersheds with the impacts on the receiving water bodies: the use of flow duration curves. Water Science & Technology. Vol. 70(1). P. 127-135. DOI: 10.2166/wst.2014.206.

Pitt, R., Williamson, D., Voorhees, J. & Clark, S. 2004. [Chapter 12:] Review of historical street dust and dirt accumulation and washoff data. In: James, W., Irvine, K.N., McBean, E.A., Pitt, R.E. (Eds.) Effective Modeling of Urban Water Systems, Monograph 13, CHI.

Pitt, R. 1999. Small Storm Hydrology and Why it is Important for the Design of Stormwater Control Practices. In: Advances in Modeling the Management of Stormwater Impacts, Volume 7. (Edited by W. James). Computational Hydraulics International, Guelph, Ontario and Lewis Publishers/CRC Press.

Pitt, R. & McLean, J. 1986. Toronto Area Watershed Management Strategy Study. Humber River Pilot Watershed Project. Final Report, Volume one. Ontario Ministry of the Environment. Toronto, Ontario, Canada.

Raudaskoski, O. 2016. Hulevesien hallintavaihtoehtojen mallinnus tiiviissä taajamassa (*Modelling urban stormwater management alternatives*). Master’s thesis. Aalto University, School of Engineering, Department of Built Environment. Espoo, Finland. 78 p.

Roesner, L.A., Bledsoe, B.P., Brashear & R.W. 2001. Are Best-Management-Practice criteria really environmentally friendly? Journal of Water Resources Planning and Management. Vol. 127. P. 150-154. DOI: 10.1061/(ASCE)0733-9496(2001)127:3(150).

Rossman, L.A. & Huber, W.C. 2016a. Storm Water Management Model Reference Manual Volume I – Hydrology. Cincinnati, Ohio. U.S. Environmental Protection Agency. EPA/600/R-15/162A. 233 p.

Rossman, L.A. & Huber, W.C. 2016b. Storm Water Management Model Reference Manual Volume III – Water Quality. Cincinnati, Ohio. U.S. Environmental Protection Agency. EPA/600/R-16/093. 161 p.

Rossman, L.A. 2015. Storm Water Management Model User’s Manual Version 5.1. Cincinnati, Ohio. U.S. Environmental Protection Agency. EPA-600/R-14/413b. 353 p.

SFTSG. 2017. StormFilter Thesis Steering Group Meeting 25.4.2017. Present: Prof. Harri Koivusalo, D.Sc. Nora Sillanpää, D.Sc. Perttu Hyöty, D.Sc. Timo Nikulainen and B.Sc. Camilla Tuomela. Sito, Espoo, Finland.

Sillanpää, N. & Koivusalo, H. 2015. Stormwater quality during residential construction activities: influential variables. Hydrological Processes. Vol. 29(19). P. 4238-4251. DOI: 10.1002/hyp.10493.

Sillanpää, N. & Koivusalo, H. 2014. Impacts of Urbanization and Event Magnitude on Runoff Contributing Area and Runoff Coefficients. Conference paper. 13th International Conference on Urban Drainage, Sarawak, Malaysia, 7-12 September 2014.

Sillanpää, N. 2013. Effects of suburban development on runoff generation and water quality. Effects of suburban development on runoff generation and water quality. Aalto University. Doctoral Dissertations, 160/2013. Espoo, Finland. ISBN 978-952-60-5374-5.

Tan, S.B., Chua, L.H., Shuy, E.B., Lo, E.Y-M. & Lim, L.W. 2008. Performances of Rainfall-Runoff Models Calibrated over Single and Continuous Storm Flow Events. Journal of Hydrologic Engineering. Vol. 13(7). P. 597-607. DOI: 10.1061/(ASCE)1084-0699(2008)13:7(597).

U.S. EPA. 1983. Results of the Nationwide Urban Runoff Program, Volume I – Final Report. Washington, DC. U.S. Environmental Protection Agency.

Valtanen, M., Sillanpää, N. & Setälä, H. 2014. The Effects of Urbanization on Runoff Pollutant Concentrations, Loadings and Their Seasonal Patterns under Cold Climate. Water, Air and Soil Pollution. Vol. 225. DOI: 10.1007/s11270-014-1977-y.

VTT. 2017. Column test results: pollutant removal capacity. StormFilter-project, work package 2: Geomaterials for stormwater filtration. Unpublished material.

Waschbusch, R.J., Selbig, W.R. & Bannerman, R.T. 1999. Sources of Phosphorus in Stormwater and Street Dirt from Two Urban Residential Basins In Madison, Wisconsin, 1994–95. Water-Resources Investigations Report 99–4021. U.S. Geological Survey. Middleton, Wisconsin, U.S.

Wenger, S.J., Roy, A.H., Jackson, C.R., Bernhardt, E.S., Carter, T.L., Filoso, S., Gibson, C.A., Hession, W.C., Kaushal, S.S., Martí, E., Meyer, J.D., Palmer, M.A., Paul, M.J., Purcell, A.H., Ramírez, A., Rosemond, A.D., Schofield, K.A., Sudduth, E.B. & Walsh, C.J. 2009. Twenty-six key research questions in urban stream ecology: an assessment of the state of the science. Journal of the North American Benthological Society. Vol. 28(4). P. 1080-1098. DOI: 10.1899/08-186.1.

Zhu, H., Xu, Y., Yan, B. & Guan, J. 2012. Snowmelt runoff: a new focus of urban nonpoint source pollution. International Journal of Environmental Research and Public Health. Vol. 9. P. 4333-4345. ISSN: 1660-4601.

List of Appendices

Appendix 1

Literature EMC sets used in simulations

Total Suspended Solids, TSS (mg/l)										
Source area	EMC set 1		EMC set 2		EMC set 3		EMC set 4		EMC set 5	
Parking areas	1660	(e	440	(e	150	(d	173	(a	44	(g
Paved Walkways	20	(e	20	(e	7.4	(d	58	(a	46	(g
Roads	242	(e	232	(b	163	(d	662	(a	64	(g
Roof	13	(e	41	(b	43	(d	27	(a	20	(g
Open Rock	11		11		11		11		11	
Stone/Tile Paving	20		20		15.8	(c	15.8	(c	15.8	(c
Sand, Gravel	810	(e	810	(e	33.7	(c	33.7	(c	33.7	(c
Vegetation, Lawns	11	(e	71	(b	12	(d	397	(a	75	(g

Total Phosphorus, TP (mg/l)										
Source area	EMC set 6		EMC set 7		EMC set 8		EMC set 9		EMC set 10	
Parking areas	0.36	(e	0.244	(c	0.244	(c	0.62	(f	1.16	(a
Paved Walkways	0.8	(e	0.8	(e	0.8	(e	0.8	(f	0.8	(f
Roads	0.62	(e	0.31	(e	0.24	(b	0.49	(f	1.31	(a
Roof	0.03	(e	0.1	(e	0.14	(b	0.04	(f	0.15	(a
Open Rock	0.05		0.05		0.07		0.2		0.2	
Stone/Tile Paving	0.36		0.162	(c	0.162	(c	0.62		1.16	
Sand, Gravel	0.2	(e	0.155	(c	0.155	(c	0.2		0.2	
Vegetation, Lawns	0.05	(e	0.05	(e	0.07	(b	0.2	(f	2.67	(a

Total Nitrogen, TN (mg/l)								
Parking areas	EMC set 11		EMC set 12		EMC set 13		EMC set 14	
Parking areas	3.1	(e	8	(c	2.2	(f	2.88	(d
Paved Walkways	1.1	(e	1.1	(e	1.1	(f	2.34	
Roads	2.4	(e	2.2	(b	1.6	(f	5.9	(d
Roof	1.1	(e	0.71	(e	0.8	(f	6.17	(d
Open Rock	1.1		1.1		1.1		2.34	
Stone/Tile Paving	1.1		0.7	(c	1.1		2.34	
Sand, Gravel	1.3	(e	1.6	(c	1.3	(f	2.34	
Vegetation, Lawns	0.94	(e	0.95	(b	1.3	(f	2.34	(d

Lead, Pb (µg/l)						
Source area	EMC set 15		EMC set 16		EMC set 17	
Parking areas	250	(e	137	(d	22	(a
Paved Walkways	80	(e	107	(d	17	(a
Roads	180	(e	170	(d	55	(a
Roof	30	(e	69	(d	21	(a
Open Rock	30		107		17	
Stone/Tile Paving	80		107	(d	17	
Sand, Gravel	30	(e	107		17	
Vegetation, Lawns	0	(e	9	(d	17	

Copper, Cu (µg/l)						
Source area	EMC set 18		EMC set 19		EMC set 20	
Parking areas	100	(e	80	(d	15	(a
Paved Walkways	20	(e	23	(d	15	
Roads	40	(e	97	(d	56	(a
Roof	100	(e	153	(d	15	(a
Open Rock	20		23		15	
Stone/Tile Paving	20		23		15	
Sand, Gravel	20	(e	23	(d	15	
Vegetation, Lawns	0	(e	11	(d	13	(a

Zinc, Zn (µg/l)						
Source area	EMC set 21		EMC set 22		EMC set 23	
Parking areas	520	(e	400	(d	450	(f
Paved Walkways	60	(e	585	(d	60	(f
Roads	180	(e	407	(d	160	(f
Roof	320	(e	370	(d	310	(f
Open Rock	40		585		40	
Stone/Tile Paving	60		585		40	
Sand, Gravel	40	(e	585	(d	40	(f
Vegetation, Lawns	0	(e	80	(d	40	(f

References

a) Bannerman *et al.* (1993)
b) Duncan (1999)
c) Gilbert & Clausen (2006)
d) Göbel *et al.* (2007)
e) Heaney *et al.* (1999)
f) Pitt & McLean (1986)
g) Waschbusch *et al.* (1999)

Appendix 2

Simulated pollutant load distributions